Radio Frequency Detection and Analysis of Synthetic Particles

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Abstract — Radio-frequency (RF) measurements provide a potentially label-free approach for quantitative analysis of cells and particles in microfluidic channels. We demonstrate an interference based RF sensor which operates from 5 MHz to 2 GHz at high sensitivity. Millimeter-sized gold and amazonite particles show particle position, size, and material strongly affect quantitative RF measurements. Lossy materials do not significantly reduce the effective quality factor, which is as high as 30,000 at 1.2 GHz, of the sensor. Thus, the sensor is particularly suitable for biomedical applications such as skin cancer detection and the development of novel label-free and all electronic rheological instrumentation.

Index Terms — Microwave sensors; coplanar waveguide;

I. INTRODUCTION

Radio frequency (RF) detection and analysis of single cells in microfluidic channels are actively explored as a label-free approach for micro-total-analysis system (μ-TAS) development [1]. Coplanar waveguide (CPW) is a popular choice for RF sensing structures, due to its fabrication convenience and broadband capabilities [2, 3]. Nevertheless, cell size and shape vary among cells. So do their positions in the sensing zone, as shown in Fig. 1. Therefore, the effects of these factors on quantitative RF detection and characterization are of great interest. Unfortunately, it is difficult to accurately place a single cell at a given position, and keep the cell still during RF measurements. If measured dynamically, then the cell position in the microfluidic channel needs to be simultaneously tracked and determined, for which there is a lack of appropriate techniques. Optical particle-tracking in bulk rheology and microrheology [4] is a possible choice. But the vertical (y-direction in Fig. 1) resolution is limited. Besides, the correlation between RF measurements and particle positions is very involved since both measurements may not have high temporal resolutions. Furthermore, CPW-based RF sensors still face sensitivity and bandwidth challenges in detecting and analyzing single cells in liquid.

The CPW sensor in [3] can trap a single cell mechanically and perform single cell broadband measurement. But the approach is not convenient for studying the effects of cell positions as well as high-speed cell sensing operations. Recently, we proposed a tunable RF sensor [5], which is promising for single cell measurement at high speed. In this work, we further develop the highly sensitive sensor by extending its operating frequency to low megahertz range and improving sensor sensitivity and stability. We also report the effects of particle position, size, and material on RF measurements.

![Fig. 1 Illustration of a coplanar waveguide sensing zone](image-url)

Millimeter size CPWs and synthetic particles are used in this effort. The large dimensions enable simple and accurate control of particle positions. The scalability of CPWs and particle diameters shows that the obtained results are instructive for single cell RF sensor development. The results also show a potential approach for developing new macrorheology instruments, where the particle size is in millimeter range, and microrheology techniques, which are important analytical tools for biomedical applications.

II. RF SENSOR DESIGN AND MEASUREMENT RESULTS

A. Sensor Design

Fig. 2(a) shows the schematic of our RF sensor. Its operation is based on an interference mechanism as discussed in [5]. In this work, cables are used to extend sensor operations to low MHz since some biological effects, such as cell membrane polarization (Maxwell Wagner) [6] occur there. The mechanical and electrical stabilities of the sensor are improved by mounting the sensor components on a thick wooden plate. Duroid high-frequency laminate 5870 are used to build CPWs, Fig. 2(b). The well on top of the CPW is constructed out of borosilicate glass. This well is filled with de-ionized water. Unused portions of the CPW are covered with thick...
polydimethylsiloxane (PDMS) sheets to minimize disturbances from microparticles in the environment and to further improve sensor stability.

![Diagram of the radiofrequency sensor setup]

Fig. 2(a) Schematic of our radiofrequency sensor (b) A photo of the sensing zone with the CPW and particle to be tested. The dimensions of the CPW are \( W = 2 \text{mm} \), \( S = 0.5 \text{mm} \), \( L = 55.6 \text{mm} \). The well dimensions are 10 by 15 mm with 16 mm height and a wall thickness of 1.29 mm.

Fig. 3 shows the measured S21 magnitude from \( \sim 5 \text{ MHz} \) to \( \sim 2 \text{ GHz} \) at a few frequency points. Thus the sensor covers a wide frequency range. The curves are obtained by taking 3 measurements at each frequency point every 20 seconds, as shown in 3(b). The minimum S21 values indicate the achievable sensitivity of the sensor if the insertion loss of the circuit components in Fig. 2 is negligible. The highest effective quality factor, calculated with \( Q = f_0 / \Delta f \text{dB} \), is \( \sim 30,000 \) at 1.21 GHz. The value is much higher than any coplanar resonator reported so far, especially when lossy materials are loaded. Nevertheless, Fig. 3(b) shows system instability for high sensitivity operations. Higher frequencies allowed for higher achievable sensitivities when testing with the current setup. Thus, in measuring particles below, S21 magnitude is intentionally tuned to \( \sim -70 \text{ dB} \) for a few reasons. First, the sensor is very stable at this level. Secondly, the RF sensor sensitivity is still high and allows convenient investigations with various particles. In fact, the sensitivity at \(-70 \text{ dB}\) is much higher than of most RF sensors reported so far with lossy materials.

**B. Particle Measurement Results**

The mm particles are first visually aligned with the center of the CPW signal line under a microscope. The vertical distance between the particle and the CPW is calibrated at the point they contact with a mirror and the microscope. A micromanipulator is used to adjust the positioning of the particles with an accuracy of 12.7 micrometers. Three types of particles are tested. They are a 2.40±0.05mm amazonite particle with a 0.616mm hole, a 2.00±0.01mm gold particle with a 0.925 mm hole, and a 3.02 ±0.03mm gold plated particle with a 1.017mm hole.

During RF measurements, the particles begin at 50.8 μm above the CPW surface, then move in x direction (Fig. 1) from the center, pass the gap, and move back to the

![Graphs showing S21 magnitude vs. frequency]

Fig. 3(a) Measured \( S_{21} \) (magnitude), (b) A zoom in view at a frequency point of 1.21GHz. \( \Delta f = f - 1.21 \text{GHz} \)

Fig. 4(a) \( |S_{21}| \) of amazonite at 3-x positions, \( y = 0.55 \text{ mm} \), and in water at 2.2 GHz. (b)The frequency and magnitude of \( |S_{21}| \) at 2.2 GHz. \( \Delta f = f - 2.2 \text{GHz} \)

Fig. 5(a) \( |S_{21}| \) of amazonite at 3-x positions, \( y = 0.55 \text{ mm} \), and in water at 580 MHz (b)The frequency and magnitude of \( |S_{21}| \) at 580MHz \( \Delta f = f - 580 \text{MHz} \)
starting position. Data are recorded every 254 μm. The measurements are repeatable and reliable. This process is repeated for heights of 177, 304, 431, and 558 μm.

When the reference branch in Fig. 2(a) is turned off (i.e. high attenuator attenuation), the RF measurement is effectively performed with a single straight CPW. The corresponding S21 is around -10 dB, which indicates an insertion loss of 4 dB. Moving the particles along x and y directions does not induce measurable S21 changes. This indicates that a simple CPW line does not have the sensitivity for our targeted measurements.

Fig. 4(a) present some frequency-domain measurement traces of a 2 mm amazonite particle at 3 different horizontal positions. Fig. 4(b) summarizes the measurement results by plotting the frequency and magnitude of S21. As expected, it shows that the particle positions affect the measurements significantly. Measurements of the same particle at 595 MHz are shown in Fig. 5(a) and 5(b). Similar trends, but at smaller magnitudes is observed. Different RF field distribution at different frequencies is probably the main reason for the differences in magnitude.

Fig. 6 shows the results with a 2 mm diameter gold particle at different vertical positions when x=0. It shows high sensitivity to vertical positions.

Fig. 6 The frequency and magnitude of |S21| vs height at 2.22 GHz for 2mm gold particle Δf=f-2.2GHz

III. DISCUSSIONS AND CONCLUSIONS

RF measurements in air, i.e. no water is included in the well in Fig. 2(b), are also conducted. Corresponding variations are similar to those in Figs. 4-6, but at smaller magnitudes. The main reason is that water serves as a high permittivity superstrate layer, which induces higher RF fields in water [7].

For single cells in microfluidic channels, the dimensions in Fig. 1 would be 100-200 times smaller than those in Fig. 2. Similar results are expected due to the scalability of CPW dimensions and RF fields. Preliminary HFSS simulation which qualitatively agree with our experiments for mm size particles, indicate smaller, yet significant, variations. Shorter particle length in z direction (Fig. 1) is probably a main reason for smaller variations.

In summary, we demonstrate the operation of an interference based RF sensor from 5 MHz to 2 GHz at high sensitivity. Lossy materials do not significantly deteriorate the effective quality factors. Thus, the highly sensitive sensor is especially suited for biomedical applications. Millimeter amazonite particles and gold particles are used to investigate the effects of particle position, size and material on RF measurements. The results show that these factors strongly affect RF measurements, which indicates the importance of position control in quantitative RF measurements. On the other hand, the sensors are promising for many other biomedical applications, such as skin cancer detection [8]. At the same time, tracking values and frequency of |S21| may provide a new approach for developing label-free and all electronic rheology instrumentation.

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REFERENCES