Microfluidics Integrated Microwave Sensors in Tandem with Optical Microscopy for Sizing and Material Classification of Single Cells and Microplastics

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ABSTRACT

Microwave sensors can probe intrinsic material properties of analytes in a microfluidic channel even at high ion concentrations since electrical screening effects cease to be dominant at microwave frequencies. While microwave sensors have been used to detect cells and microparticles in earlier studies, the synergistic use and comparative analysis of microwave sensors with optical microscopy for material classification and size tracking applications have been scarcely investigated so far. Here we combined microwave and optical sensing to differentiate microscale objects based on their dielectric properties. We also show that standalone microwave sensors can track the relative changes in cellular size in real-time. These findings demonstrate that microwave sensing technology can serve as a complementary technique for microscale pollutant screening and single-cell biophysical experiments.

INTRODUCTION

Dynamical sizing and material characterization of microscopic particles, such as microplastics and cells, continue to occupy a central role in environmental and biological sciences. For the detection of microplastics in the environment,1,2 optical microscopy analysis is often used as the first step for feature selection, followed by FT-IR or micro-Raman analysis for material classification. In personalized medicine, precise monitoring of cellular size at high speed has opened avenues for the early diagnosis of diseases3-6. While optical microscopes are ubiquitous in laboratories, a system with a smaller form factor, lower cost and ease of use is often needed for point-of-care applications. This need has driven a significant amount of research efforts for developing sensors capable of sizing single cells and particles through measuring either the mass7-18 or electrical properties, such as impedance change at the high frequency band19-27 or capacitance at microwave frequencies.28-35

Critically, the size measurement in each approach (optical, inertial, capacitive) yields a different physical parameter. With bright-field optical microscopy, the geometrical volume of an object can be extracted (e.g., by estimating the volume through diameter measurements and assuming spherical shape for objects). On the other hand, mass and capacitance sensors provide outputs that depend not only on the geometrical volume but also on the intrinsic parameters of the object as well — mass density and dielectric permittivity, respectively. In principle, such intrinsic parameters can be used for material classification. Especially, the use of electrical
permittivity can form the basis of a robust differentiation approach between microplastics vs. cells (and other particles of biological origin), since there is a large difference in the relative permittivity values between the two groups (2-3 vs. ~40-60 respectively\textsuperscript{36, 37}). To obtain permittivity values, one potential avenue is to combine capacitive and optical measurements, so that the volume of the object can be factored out of the capacitance signal.

The electrical capacitance of a cell is related to the total polarizability of the material accumulated inside it. As a cell synthesizes proteins and biological polymers, such as cytoskeletal proteins and phospholipids, the polarizability of the cell is expected to become markedly different than the polarizability of its external environment.\textsuperscript{38-40} This contrast in polarizability can be measured as a change in the total capacitance of an electrical sensor. Therefore, capacitive measurements can also serve as a standalone platform for tracking relative changes in cellular size, in addition to their complementary use with optical microscopy for simultaneous sizing and material classification.

Unfortunately, when capacitive measurements are conducted at low AC frequencies, extraneous effects such as Debye screening, electrical double layer formation and membrane polarization dominate the response from the sample.\textsuperscript{41} Techniques working in this range, such as conventional impedance spectroscopy, do not directly probe electrical permittivity values of the cells. On the other hand, at electrical frequencies larger than several hundred MHz, electrolyte ions cannot follow the electromagnetic field and cease to interfere with the sample’s inherent response.\textsuperscript{28, 42} At these frequencies, hydrogen bonds in the water can still follow the electrical oscillations up to approximately 20 GHz.\textsuperscript{35} As a result, a large contrast difference emerges at the lower end of the microwave frequencies (1-20 GHz) between the extracellular medium (mainly composed of water) and the intracellular biostructures that are rich in biopolymers. As a result of this contrast difference, microwave sensors have been used to detect individual cells.\textsuperscript{17-24} With this in mind, the ability to discern material properties motivates the development of microwave sensors, as opposed to impedance cytometry which operates at lower frequencies (typically 1-50 MHz) and provides size information.\textsuperscript{19-27}

Here we demonstrate that the combined use of microwave sensor signals with geometric size measurements from optical microscopy packaged within a microfluidic platform can provide a classification technique for objects with sizes down to several microns. Analytes with similar geometric sizes, but different electrical permittivity values induce signals of different sizes in the microwave sensor. To achieve high resolution in microwave sensing, we used the combination of narrow-band detection and electric field enhancement at the sensing region. This way we showed that mammalian cells and polystyrene microparticles of similar sizes can be differentiated from each other by the combined sensing principle. We also performed continuous electrical size measurements on single cells with microwave sensors to show that the same cell can be measured repeatedly. Our results demonstrate the emerging potential of microfluidics-integrated microwave sensors (MIMS) for environmental screening and single-cell biophysical measurements.

**RESONANT SENSOR**

A microwave resonator can be used as a capacitive sensor since any changes in the capacitance of the sensor (\textit{e.g.}, a cell passing in between its electrodes) can be measured with high precision through the resonance frequency of the sensor. For small analytes, the relationship between the induced capacitance change, $\Delta C$, and the resonance frequency change $\Delta f$ can be written as: \textsuperscript{40}

$$\frac{\Delta f}{f_0} = -\frac{1}{2\Delta C/\epsilon_0}$$
where $f_0$ is the original resonance frequency of the sensor, $C_0$ is the original capacitance of the sensor. The capacitance change can be related to the parameters of the analyte and the sensor as:\textsuperscript{28,29}

$$
\Delta C = \varepsilon_{\text{fluid}} 4\pi r^2 K_{CM} \left( \frac{E_{rms}^2(r)}{U_{rms}^2} \right)
$$

Here, $\varepsilon_{\text{fluid}}$ is the dielectric permittivity of the host fluid, $r$ is the radius of the analyte, $K_{CM}$ is Clausius–Mossotti factor which depends on the permittivity values of the analyte and fluid:

$$
K_{CM} = \frac{\varepsilon_{\text{analyte}} - \varepsilon_{\text{fluid}}}{\varepsilon_{\text{analyte}} + 2\varepsilon_{\text{fluid}}}
$$

Finally, $U_{rms}$ denotes the root-mean-squared voltage applied to the sensor and $E_{rms}(r)$ is the electric field at the analyte location. Importantly, increasing the electric field, for instance by decreasing the gap between capacitive electrodes, increases the size of the signal.

To utilize the high sensitivity of microwave frequencies, we designed and fabricated two sensors based on two different microwave resonator topologies: Sensor 1 is a bowtie coplanar waveguide (CPW) resonator (Figure 1a), while Sensor 2 is a Split-Ring Resonator (SRR). Both sensors are fabricated on a fused silica chip and contain active sensing regions where the gap between metal electrodes narrow down (50 $\mu$m for sensor 1, and 30 $\mu$m for sensor 2). The geometric parameters of the two sensors are detailed in SI Figure 1. In the active sensing region, the inter-electrode distance shrinks to intensify the local electric field which enhances the detection sensitivity (Figure 1a). As cells and microparticles pass through the sensing region one by one, they induce distinct frequency shifts in the microwave sensor signal while being imaged by optical microscopy (Figure 1b, c).

**Figure 1.** (A) Overall schematic of the system (Sensor 1): while microwave sensor data was being recorded, the sensing region was simultaneously monitored via an optical microscope. The image shows the CPW resonator configuration. A PDMS-based microfluidic channel was
bonded to the fused silica wafer and oriented so that the flow passes through the active region of the sensor. (B) Typical microwave resonator response observed during the transition of single cells (MDA-MB-231-Luc2-GFP). Each precipitous spike is induced by a single cell (C) Similar to (B), but with single polystyrene particles (20 µm nominal diameter) passing through the sensing region.

**EXPERIMENTAL SETUP**

The experimental setup is composed of three subsystems: 1) the MIMS device for microwave measurements of single cells and microparticles, 2) an optical microscope for independent, optical size measurements, and 3) a fluidic control system that transfers cells to the sensing region (Figure S3). The microwave characteristics of each MIMS device (such as the resonance frequency and Quality Factor) were first measured using a vector network analyzer (Figure S4). After this initial characterization, we performed single-particle measurements by using a custom electronic setup which is based on narrow-band detection to increase the sensitivity of the MIMS. In this scheme, narrow-band detection of the resonance frequency was performed with phase-sensitive detection through a lock-in amplifier. Since the maximum operation frequency of the lock-in amplifier was below the microwave resonance frequency, we constructed an external heterodyne circuitry to continuously track the resonance frequency (Figure S5). In this scheme, the phase angle of the resonator response function was locked to 0 degrees (i.e. the phase value at resonance) with a proportional-integral (PI) controller to form a Frequency-Locked Loop (FLL). Any deviation of phase away from 0 degrees emerged as an error signal which was used to update the frequency of the signal generator. With this method, we can continuously track the resonance changes with high precision.

The fabricated MIMS chip, together with microwave and microfluidic components, was placed on the sample stage of a fluorescence microscope. While the sensing region was observed by optical microscopy, mammalian cells (MDA-MB-231-Luc2-GFP) and polystyrene microparticles of varying size (10 µm or 20 µm diameter) and composition (non-magnetic, magnetic and superparamagnetic) were transported through the active region in separate runs (Methods). To transport the analytes, we used a controllable pressure pump (Flui gent; MFCS-EZ) with typical flow rates of 0.3 - 1 µL/min. These flow rates were chosen so that accurate optical images of cells can be obtained as they passed through the sensing region.

**EXPERIMENTAL RESULTS**

**PARTICLE AND CELL CHARACTERIZATION EXPERIMENTS**

For sensor 1, the resonance frequency (at 2.7 GHz) was monitored with an Allan deviation of $4 \times 10^{-8}$ and frequency modulations induced by single cells crossing the sensing region were recorded. The shift in the first resonance mode, which corresponds to the electrical volume of a cell, can be related to the geometrical size of a cell (Supplementary Note 1). While microwave data were being measured, a video for the cells transiting through the sensing region was recorded simultaneously to correlate the optical and microwave signals (Supplementary Video 1). We calculated the geometric volume of the cells and polystyrene microparticles from microscopy images, assuming a spherical shape. We then plotted the geometrical size vs. the corresponding microwave frequency shifts to summarize the data in both dimensions (Figure 2A).

As expected, the optical size of the mammalian cell sample spanned a large range; microwave sensor response followed the same trend in an almost linear manner. The data for polystyrene particles were concentrated around the nominal value of the sample (20 µm). Importantly, the data clusters for polystyrene and cells were well separated from each other. Dashed lines show the expected trend for frequency shifts of the analytes as a function of volume (with relative
The permittivity of polystyrene taken to be $\varepsilon_r = 3^{45}$ Supplementary Note 1) and they closely match the experimental results. It is clear from Figure 2A that a polystyrene particle generates a frequency shift in the microwave sensor several times larger than the frequency shift induced by a cell of similar size. We attribute the dominant factor behind the dispersion in the frequency shift data to be the height dependency of the microwave sensor response as the Electric field distribution is non-uniform (Figure S2).

To demonstrate the general applicability of material classification using microwave resonators, we conducted a similar experiment with sensor 2 (the SRR device at 4.2 GHz with Allan Deviation of $7.5 \times 10^{-7}$). As before different analytes populated distinct regions in the analytical space formed by optical volume and microwave resonance shift (Figure 2B). Polystyrene particles generated much larger microwave signals compared to cells of the same optical size.

The microwave signal induced by each analyte depends on how much its permittivity differs compared to the permittivity of the culture media ($\varepsilon_r \sim 78$). More specifically, the signal is proportional to the particle volume and Clausius-Mossotti factor: $^{17}$

$$\Delta f_{\text{Microwave}} \sim V_{\text{particle}} K_{CM}(\text{particle})$$

The Clausius-Mossotti factor of polystyrene ($\sim 0.5$) is several times larger compared to that of cells ($\sim 0.1$). Hence, we expect a much larger microwave signal amplitude for undoped polystyrene particles compared to cells with similar size. Further, polystyrene particles doped with magnetic materials (iron oxide) results in a further increase in the observed frequency shifts (Figure 2B, and Table S2). While the geometric size difference between the superparamagnetic and non-magnetic polystyrene particles is small, their microwave response differs almost by a factor of two. Overall, the trend clearly indicates that differentiation of analytes with different compositions is made possible by the combined sensing technique.

**Figure 2.** (A) Experimental and analytical results obtained by CPW resonator. For cells, we observe a linear relation between optical volume of the cell and microwave frequency change. Large contrast in the dielectric constant can be observed between polystyrene particles and cells having a similar optical volume (blue highlighted region) (B) Same experiment was performed using SRR design with different particles. The same linear relation for the cells can be observed and each type of analyte spans a different region on the analytic plane of optical volume – microwave frequency change. In all cases, the marker sizes are larger than the uncertainties in the single cell/particle measurements. Insets: (A) the active region of Sensor 1 with a cell under fluorescent microscopy; (B) the active region of Sensor 2 with a 20 µm polystyrene particle.
SINGLE-CELL TRAPPING EXPERIMENTS

After the simultaneous use of both optical microscopy and microwave sensing, we decided to benchmark the size quantification performance of our microwave sensor in the light of standard fluorescence microscopy. A single cell can be trapped and made to pass back and forth between the sensing electrodes by fine-tuning the applied microfluidic pump pressure dynamically (Supplementary Video 2). The fluorescent optical images of the same cell were recorded during the experiments and then processed by a custom image processing algorithm (Table S1). The algorithm counts the number of white pixels for 20 consecutive frames and estimates the mean and standard deviation in the geometrical size of the cell. This way, the transition position, dwelling time and velocity of the cell can be obtained (Figure S8A) while recording its microwave response in real-time (Figure S8B).

By recording data for 25 minutes and continuously reversing the applied fluidic pressure, we found that the mean value for the frequency shift was 4.87 kHz (for a resonance frequency of 2.51 GHz) with a normalized standard deviation of 0.09, where normalized standard deviation, $\sigma_{MW}$, is defined as the standard deviation over the mean (Figure 3). The data does not indicate any directional asymmetry of the sensor for the cell moving forward or backward.

The geometric size of the trapped cell was estimated by the image processing algorithm and compared with the frequency shift statistics. We expected the algorithm to yield similar volume values as the same cell was processed in different frames. In fact, in Figure 3, the volume of the cell is concentrated around $1.18 \times 10^4 \mu m^3$ with a standard deviation normalized to the mean value ($\sigma_{opt}$) of 0.17, which can be seen at the bottom histogram. Remarkably, the microwave sensor results indicate a relatively narrower distribution for the size of the cell ($\sigma_{MW} = 0.09$ for microwave versus $\sigma_{opt} = 0.17$ for optical measurements).

![Figure 3](image)

**Figure 3.** Comparison of the size distributions obtained from frequency shift measurements and through fluorescence microscopy. There are 171 individual passes from the sensing region, the histograms for volume and frequency shifts are also projected to their respective axes, and in both cases a distinct peak appears as expected.
MEASURING CHANGES TO CELL SIZE IN REAL-TIME

The ability to dynamically monitor the effects of drugs and chemicals delivered to diseased cells is of utmost importance. One such dynamical effect is the change in electrical size of a cell, which can be detected by MIMS. To this end, we designed another experiment to detect the change in electrical size of a single cell by tracking the resonance frequency of sensor 1. As shown in the previous section (Figure 3, S8B, S9), the uncertainty in a single cell size measurement was found to be approximately 9% of the mean size of the cell in the previous experiment, so changes in size larger than this can be monitored.

To demonstrate that microwave sensors can track the real-time dynamics of individual cells, we chose to use dimethyl sulfoxide (DMSO), an osmolyte chemical that has been shown to affect cell volume through inducing shrinkage and swelling. DMSO is also known to have mild toxic effects on cells which scale with the concentration of DMSO, so we expected to see those effects on cell represented in the changes in electrical volume. We observed that the effect of DMSO is maximized when treating the cells for approximately half an hour in their culture plate with a 50% concentration of DMSO. For the experiment, cells were pretreated with DMSO for 15 minutes to kickstart cell changes. After the pretreatment, the cells were transferred to the microchannel in a 1:1 cell medium to DMSO solution, and a target cell among the population was selected and trapped within the sensing region by controlling flow direction while microwave data was being recorded (Figure 4).

![Figure 4](image-url)

**Figure 4.** The trend in the frequency shifts when a target cell was treated with DMSO or not and continuously measured within the sensing region. (A) Cells were pretreated with DMSO for 15 minutes. The ten points moving average of the shift was 6.43 kHz at the beginning, later, declined to 4.64 kHz after half an hour (B) Control run with the same device. This time cells were treated with the culture medium instead of DMSO for 15 minutes and the change in the signal average remained close to initial levels (5.46 kHz to 5.11 kHz).

As DMSO causes a contraction of the interfacial region between water-lipid boundary, we expected to see a shrinkage in the lipid bilayer of the cells causing size to decrease. Indeed, the ten-points moving average of the frequency shifts decreased from 6.43 kHz to 4.64 kHz (Figure 4A) within thirty minutes (28% decrease, well beyond the uncertainty in size measurements). For the control run, the same cell line in another culture dish with the same passage number was processed in the same way, replacing DMSO with culture medium. Using the same device and same experimental conditions, another cell from the control population was tracked for more than twenty minutes. Throughout the experiment, the average frequency shift remained close to the original signal level as depicted in Figure 4B (5.46 kHz to 5.11 kHz, a decrease of %7 which is within the measurement uncertainty level).
We performed verification measurements using flow cytometry on cell samples treated with DMSO as outlined above. First, we verified that after a total of 30 min exposure to DMSO, the cells showed a decrease in viability (84.0%) compared to negative control cells (95.7%) as shown by Propidium Iodide (PI) assay. The increase in side-scatter (SSC) value which is a measure of cellular granularity was most prominent for DMSO treated cells compared to the negative control (Figure S12), while the change in front-scattering (FSC) which is correlated to geometric size was small between the two samples. The change in the electrical size being measured seemed to track SSC but was inconclusive in the case of FSC. Since internal electrical permittivity contributes to the value of electrical size, the measured change in frequency might have been linked to internal changes in the cell due to its exposure to chemical injury (by DMSO) captured as an increase in SSC measurements. In this case, the tracking of electrical size makes it possible to detect early cellular injury before changes in size or morphology are detected through optical microscopy.

**CONCLUSION**

In conclusion, we have shown several proof-of-concept utilities of microwave sensors in different sensing scenarios. When microwave sensors are used in conjunction with optical microscopy, both the geometric size of a particle and electrical capacitance change induced by the same particle can be obtained simultaneously. With the two-dimensional analytic information, it becomes possible to distinguish particles of different material compositions based on their intrinsic dielectric properties. Furthermore, standalone microwave sensors can be used to track the internal changes before they are manifest visually. These results indicate that microwave sensors can add a unique analytical dimension for material screening and single-cell biophysics experiments.

**METHODS**

**Microwave Measurement.** The resonance frequency of the chip was determined considering the S21 response of the sensing region with circulator (PE8401) on the vector network analyzer (Rohde & Schwarz ZNB40). The driving signal (around 2 - 3 GHz) from the signal generator (Rohde & Schwarz SMB 100A) was first up-converted with the output signal (2 - 3 MHz) from the lock-in amplifier (Zurich Inst. MFLI). Then, the signal was sent to the circulator to effectively drive and read the response of the resonator. Similarly, the response was down-converted and filtered with a low pass filter (MiniCircuits 4.5 MHz)

**Optical Size Measurements.** To obtain the optical size of each cell under bright field microscopy, the number of pixels inside each single cell was estimated digitally using polyarea function of MATLAB. The pixel size was matched to the dimensions of the device on the same image. The mean and standard deviation of the size of each cell/particle was obtained by measuring the same cell on many successive frames. The pixelated area was then converted first into the geometric area, and then assuming a spherical shape, into the volume of the particle/cell. For fluorescent cell analysis, image processing algorithm is explained in Supplementary Note 3.

**Cell Culturing.** MDA-MB-231 was purchased from ATCC (Manassas, VA, USA) and was labeled with green fluorescent protein (GFP) to be able to visualize under fluorescent light. Cells were cultured in Dulbecco’s modified Eagle’s medium (Biowest, Nuaille, France), supplemented with 10% fetal bovine serum (FBS, Biowest), 1% non-essential amino acids (Biowest) and 50 U/ml penicillin/streptomycin (P/S, Biowest). For the standard experiments, cells were washed with phosphate-buffered saline (PBS, Biowest) and trypsinized (Biowest) to detach from the plates. The suspended cells were added to a reservoir, and trypsin was neutralized by adding cell medium. The cells were then transported to the sensing region with a controllable pressure pump (Fluiagent; MFCS-EZ) and passed through a flow sensor with...
typical flow rates of 0.3 - 1 µL/min. To assess the changes in the size of the cells, cells were pre-treated with 100% pure DMSO (ChemCruz, TX, USA) and growth medium (DMEM) as a control group for 15 minutes and then collected for the analysis.

**Polystyrene Samples:** We used 10 ± 0.15 µm polystyrene particles (Sigma-Aldrich, Supelco - 72822), 20 ± 0.3 µm polystyrene particles (Sigma-Aldrich, Supelco - 74491), 10 ± 0.15 µm superparamagnetic polystyrene particles (Sigma-Aldrich, 41110) and 10 ± 0.15 µm paramagnetic polystyrene particles (Sigma-Aldrich, 49664) which constitutes a more homogeneous sample compared to a cell culture. We diluted the original solution with deionized water at a ratio of 100:1. A cell solution was suspended following the same steps in the previous experiments of Figure 2. Both microparticle and cell experiments were performed using the same device.

**SNR Calculations.** In experiments with 20 µm polystyrene particles (Sigma-Aldrich, Supelco - 74491), for each channel height, the maximum frequency shifts induced by each particle \((f_i)\) is measured. The mean frequency shift is calculated as \(\bar{f} = \frac{1}{N} \sum_{i=1}^{N} f_i\) where \(N\) denotes the number of microparticles measured for a given channel height (for all cases \(N>50\)).

The Ensemble Standard Deviation (\(\sigma\)) is calculated as \(\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (f_i - \bar{f})^2}\). Noise Level is obtained by calculating \(\sqrt{2} \times \sigma_A(\tau_{FLL})\) where \(\sigma_A(\tau_{FLL})\) stands for the Allan Deviation at the FLL time scale \(\tau_{FLL}\), just prior to introducing microparticles into the sensor. SNR in frequency shift is calculated as the mean frequency shift over the noise level. SNR of the Ensemble is calculated by dividing the Mean Frequency Shift to Ensemble Standard Deviation. The dispersion of the commercial microparticle sample is reported as \(\sigma_R = 0.3 \mu m\) in diameter, with a mean diameter of \(R = 20.1 \mu m\). The microwave frequency shift signals are proportional to the mass (and not the radius) of the microparticles. The mass of the microparticles scales as the cube of the diameter (\(m \sim R^3\)), hence the standard deviation of the mass distribution (\(\sigma_m\)) is \(\sigma_m = 3\bar{m} \times \frac{\sigma_R}{\bar{R}}\). Here, \(\bar{m}\) denotes the mean value for the mass, and the relationship is obtained by using standard formulas for relating the variances of random variables with narrow distributions. Plugging in the numbers, \(\frac{\sigma_m}{\bar{m}} = 3 \times \frac{0.30 \mu m}{20.1 \mu m} = 0.045\). As a result, the SNR that can be obtained from this sample cannot be larger than \(\frac{\bar{m}}{\sigma_m} = 22.3\).

| Channel Height [µm] | Mean Frequency Shift [kHz] | Noise Level [kHz] | Single Event Resolution | Ensemble Standard Deviation [kHz] | Ensemble Resolution |
|---------------------|-----------------------------|-------------------|-------------------------|-----------------------------------|---------------------|
| 35                  | 40.4                        | 0.325             | 124                     | 2.26                              | 17.9                |
| 55                  | 28.9                        | 0.291             | 99.2                    | 2.13                              | 13.6                |
| 110                 | 12.8                        | 0.096             | 134                     | 1.18                              | 10.8                |

The effect of channel height on frequency shifts. Particle was trapped between the electrodes in each case and their responses were recorded. As the channel height was increased, the
intensity of the electric field was reduced (Figure S2) and the responsivity of the device decreased. In all cases, at least 50 nominally identical particles were flown through the active region. By using the maximum frequency shifts induced for each particle for a given channel height, Mean Frequency Shift and Ensemble Standard Deviation are calculated. Noise Level is obtained by calculating $\sqrt{2} \times \sigma_A(\tau_{FLL})$ where $\sigma_A(\tau_{FLL})$ stands for the Allan Deviation of the device for the FLL timescale, $\tau_{FLL}$, just prior to introducing microparticles into the sensor. SNR in frequency shift is calculated as the mean frequency shift over the noise level. SNR of the Ensemble is calculated by dividing the Mean Frequency Shift to Ensemble Standard Deviation.

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Author Contributions

AS, UT, BS, HDU, HSP and HA performed the microwave/microfluidics measurements. HSP, AS and UT performed the microfabrication of the devices. OA, AS, HA and HDU carried out the cell protocols in consultation with OS. AS, RTE and BK, BS conducted data analysis and simulations. OS and MSH supervised the research project. All authors contributed to the writing of the manuscript.

COMPETING INTEREST

MSH is a co-founder of Sensonance. The other authors declare no competing interests.

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