A radio frequency device for measurement of minute dielectric property changes in microfluidic channels

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We demonstrate a sensitive radio frequency (rf) device to detect small dielectric property changes in microfluidic channel. The device consists of an on-chip Wilkinson power divider and a rat-race hybrid, which are built with planar microstrip lines and thin film chip resistors. Interference is used to cancel parasitic background signals. As a result, the measurement sensitivity is improved by more than 20 dB compared with conventional transmission lines. Compared with an ultrasensitive slot antenna/cuvette assembly [K. M. Taylor and D. W. van der Weide, IEEE Trans. Microwave Theory Tech. 53, 1576 (2005)], the proposed rf device is two times more sensitive. © 2009 American Institute of Physics. DOI: 10.1063/1.3072806

Measuring dielectric property changes has been developed and used as an effective approach to investigate biological matter and processes, such as protein thermal unfolding and refolding, lipid bilayer membranes, large aqueous-based molecules, and cells. It has also been developed for bioanalysis. Sensors that are based on measuring dielectric property changes, such as surface moisture sensors, have been demonstrated as well. In comparison with other approaches, measuring dielectric properties and their changes (i.e., dielectric spectroscopy) electronically has several advantages. It provides a relatively simple electronic way to gain information about the subject without the need for labeling, chemical modification, or physical intrusion. In addition, electronic methods are compatible with other sensor techniques and hold the potential for parallelization and integration.

Transmission lines and antennas are two main high-frequency structures developed and used for dielectric property measurements. A slot antenna/cuvette assembly had a sensitivity that is ~30 times higher than that of fluorescence spectroscopy, which is the most sensitive method popular for protein thermodynamics characterization. Resonant frequency shift was used in Ref. 1 as an indicator of dielectric property changes. For planar transmission line structures, elastomer polydimethylsiloxane (PDMS) microfluidic channels are usually developed since most biospecimens and bioprocesses naturally exist and occur in an aqueous environment. Some recent efforts are coplanar waveguide (CPW) transmission lines for submicroliter fluid sample measurement, dielectric heating effect investigations, single cell studies, and on-chip CPW for biological cell characterization and analysis. However, the sensitivity of these transmission line based approaches is relatively limited due to background signals that come from the lines. These background signals are usually strong, yet necessary for sample probing and signal transduction. In this letter, we demonstrate an on-chip rf device that uses interference with planar transmission lines to improve dielectric property measurement sensitivity. The method was initially proposed and briefly discussed in Ref. 13.

Figure 1 is a schematic of the proposed high sensitivity rf device. An incoming signal from port 1 is split evenly via a 3 dB Wilkinson power divider into two branches. The 100 Ω resistor of the Wilkinson power divider will absorb reflected signals from any structure discontinuities and provide isolation between the two branches. Signals transmit across the material under test (MUT) channel and reference material (REF) channel, and then propagate to the 180° rat-race hybrid and arrive at port 2. Port 3 is terminated by a 50 Ω resistor. Assuming low-loss transmission lines with propagation constant γ = α + jβ, the measured scattering parameter, S21, at deign frequency is

\[
S_{21} = \begin{bmatrix} \exp[-\alpha \sum_{i} l_i - j(\sum_{i} \beta l_i)] \\
S_{21}^{\text{power divider}} \times S_{21}^{\text{hybrid}} \\
\times \left[S_{21}^{\text{MUT}} - \exp(-\alpha/2)S_{21}^{\text{REF}}\right]
\end{bmatrix}
\]

where \(S_{21}^{\text{MUT}}\) is the scattering parameter of the transmission line section on which the MUT PDMS channel is attached, and \(S_{21}^{\text{REF}}\) is for the transmission line section on which the REF PDMS channel is attached.

When loss difference \[\exp(-\alpha/2)\] between the \(\lambda/4\) section and \(3\lambda/4\) section of ring hybrid is small, two signals coming from the top path and the bottom path will cancel

![FIG. 1. (Color online) Schematic of the proposed high sensitivity rf sensing device. The dotted and dashed lines indicate two main signal paths. The dashed boxes indicate the attached PDMS microfluidic channels for material under test (MUT) and reference material (REF).](image-url)
each other provided that $S_{21}^{\text{MUT}} = S_{21}^{\text{REF}}$, i.e., the two PDMS channels are filled with the same materials. Then $S_{21} = 0$. If $S_{21}^{\text{MUT}} \neq S_{21}^{\text{REF}}$, their difference will appear at port 2, then $S_{21} \neq 0$. As a result, the background signals are canceled and small differences between the MUT and REF materials are detected.

The fabricated rf device is shown in Fig. 2 with PDMS microfluidic channels. The designed operating frequency is 6 GHz. A 4 in., 500 μm thick Corning Pyrex 7740 wafer was used. Its dielectric constant is 4.6 with a loss tangent of 0.004 at 20 °C and 1 MHz, respectively. Due to design and process convenience, microstrip lines, instead of more sensitive CPW, were designed and fabricated for the device. The lines were formed with chromium/aluminum/gold metals. Thin film chip resistors were attached to the device. Standard microfabrication procedures were used for device fabrication. The PDMS microfluidic channels were 8 mm long, 10 mm wide, and 350 μm high. Peek tubing were inserted into the inlet and outlet and glued by the UV curable epoxy for sample solution injection.

An HP8510C vector network analyzer and a Cascade probe station with ground-signal-ground probes were used to measure the scattering parameters. A full two-port calibration procedure was conducted before measurements. Two sets of primary alcohol-water mixtures were prepared with different concentrations in terms of molar fractions. The REF PDMS channel residing in the bottom path was filling with reference solution, de-ionized water in this case; the MUT PDMS channel residing in the top channel was filled with different sample solutions. The transmission scattering parameters $S_{21}$ were measured for these samples.

The results are shown in Fig. 3. Good background cancellation performance, $\sim 56$ dB, was observed when the MUT and REF PDMS channels were filled with de-ionized water (namely, $X_m$ or $X_e$=0.00). The frequency, where the $S_{21}$...
has a minimum value, is defined as \( f_m \). It shifted by 7.5 MHz from the design frequency (6 GHz) due to design and fabrication variations and the attachment of the PDMS channels. The dielectric property changes in MUT cause the frequency shift and signal level change at the design frequency. Both can be used as sensing indicators of dielectric property.

The change in frequency shift and signal level change at the design frequency. Both can be used as sensing indicators of dielectric property changes as have been in Refs. 1 and 5. The change in \( S_{21} \) (dB) is defined as \( S_{21,\text{mixture}} - S_{21,\text{water}} \), where \( S_{21,\text{mixture}} \) and \( S_{21,\text{water}} \) are the \( S_{21} \) responses when the MUT is alcohol-water mixture and de-ionized water, respectively. Figure 3(c) shows the change in \( S_{21} \) measured at operating frequency, 6 GHz, by use of our rf device and the comparison microstrip line device, both are shown in Fig. 2. Identical alcohol-water mixtures are measured by use of both devices. It is clear that our rf device is much more sensitive than the comparison line. Figure 3(d) shows the variation of frequency \( f_m \) with approximate dielectric constant \( \varepsilon' \) for alcohol-water mixtures with different molar fractions. The dielectric constant values obtained in Ref. 14 are used. It shows that the proposed rf device is two times more sensitive than the setup in Ref. 1.

A few factors affect the sensitivity of the proposed rf device. The symmetry of the device is the most important one since it determines the level of cancellation. The loss difference between the \( \lambda/4 \) and \( 3\lambda/4 \) sections is the main reason for device asymmetry that leaves residual background signals. Fortunately, this problem can be solved by adjusting the metal film thickness of the two sections. For the device in Fig. 2, the two PDMS channels are another possible major source of asymmetries since the channels are manually aligned to the rf device under the microscope. The asymmetry probably explains the deep peak in Figs. 3(a) and 3(b). A second factor is the length of the PDMS channel if we define sensitivity as the minimum detectable concentration level of the mixture. Therefore, there is a tradeoff between the volume of MUT and the device sensitivity. A third factor is the type of transmission lines that are used and the way they are used. The rf device in Fig. 2 uses the top space of microstrip lines for MUTs. This kind of arrangement is least sensitive to dielectric property changes since the rf field of the microstrip line is mainly concentrated between the signal lines and the ground. Nevertheless, the proposed rf device demonstrated great sensitivity improvement. Further sensitivity improvement is expected if MUT is placed between the signal line and the ground of the microstrip lines, such as the capacitor sensor, if CPW is used.

In conclusion, we have demonstrated a rf device that uses on-chip interference to cancel background parasitic signals. As a result, signal sensitivity is greatly improved.

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