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QUANTITATIVE PERMITTIVITY MEASUREMENTS OF NANOLITER FLUID VOLUMES FROM 50 MHZ TO 40 GHZ WITH MICROFLUIDIC CHANNELS*

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Abstract

This paper describes the development of coplanar waveguide measurement structures integrated with microfluidic channels in order to rapidly determine the broadband dielectric properties of nanoliter volumes of fluids, fluid mixtures, and colloids over the range of frequencies from 50 MHz to 40 GHz. A number of different integrated microfluidic-microelectronic structures are employed in order to quantitatively determine the complex permittivity function over this wide range of frequencies. Transmission line network models are developed that use experimentally derived parameters to de-embed the response of the fluid-loaded devices, and finite-element models relate the fluid complex permittivity to the transmission line circuit parameters.

Introduction

The electromagnetic response of fluids and fluid mixtures provide the basis for a wide number of measurement and analysis techniques. With the development of microfluidic structures, sensitive new techniques have been developed to characterize particles (nanoparticles, proteins, biomolecules) and biological cells over a wide range of frequencies, detect minute changes in dielectric properties, and to manipulate particles with electrokinetic forces. While these techniques provide valuable information of fluid and mixture electromagnetic properties, a wideband technique capable of determining the quantitative permittivity would be extremely valuable for extending the frequency range of electromagnetic characterization in microfluidic structures, or for calibrating or verifying the response of newly developed microfluidic-based devices.

We have developed a measurement technique that combines the broadband nature of coplanar waveguide transmission lines and lumped-element devices to determine the quantitative permittivity function of fluids over the frequency range 50 MHz to 40 GHz by use of microfludic channels [1]. The benefits of moving quantitative fluid permittivity measurements to the chip level include the potential to calibrate other device structures, to integrate with other analytical techniques, and to shrink broadband microwave permittivity measurements to the single-cell level.

Calibration and Measurement Structures

Our measurement structures are based on coplanar waveguide transmission lines and lumped-element structures that are calibrated and measured on-wafer by means of movable wafer probes connected directly to a vector network analyzer. We design and fabricate custom calibration structures either on the test wafer containing the microfluidic channels or on a separate reference wafer. These custom calibration structures allow us to locate the measurement reference plane directly on the test wafer, and set the reference impedance for S-parameter measurements to a constant real value.

Microfluidic channels that are typically 50 μm deep and 100 μm to 1000 μm wide are fabricated by molding using the elastomer polydimethylsoloxine (PDMS). A thick photoresist on a Si master is fabricated, and the microchannel is molded in the PDMS, which is then transferred to the measurement wafer and bonded in place. Figure 1 shows a photograph of an integrated microfluidic-microelectronic measurement structure fabricated on a quartz substrate.

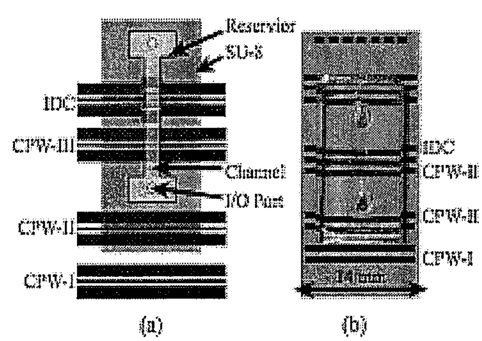

Figure 1. Integrated microfluidic-microelectronic test chips. Schematic diagram is shown in (a), while (b) shows a photograph of a finished test device. The fluid inlet/outlet ports are specified as I/O ports.

Measurement Layout and Modeling

Figure 1 shows the layout of a subset of transmission lines and devices on a test wafer. The microfluidic channel runs in a vertical direction, crossing CPW transmission lines and lumped devices that run in the horizontal direction. Fluid is injected and withdrawn from the device by use of plastic tubing connected to the inlet/outlet ports shown in the figure. The structures toward the bottom of the figure are used to determine the broadband properties of the quartz substrate and the PDMS.

We model the fluid-loaded transmission lines using the network model shown in Fig. 2 [2]. This approach allows us to determine the necessary electrical parameters of the different transmission line segments from independent measurements. We implement the model shown in Fig. 2(b) using transmission, or T-parameters, which allows us to easily de-embed the region of the fluid-loaded transmission line from the measured S-parameters of the composite structure, once the relevant properties of the other regions are determined by independent measurements. This approach also allows us to include interface effects between uniform transmission line regions using additional T-matrices.

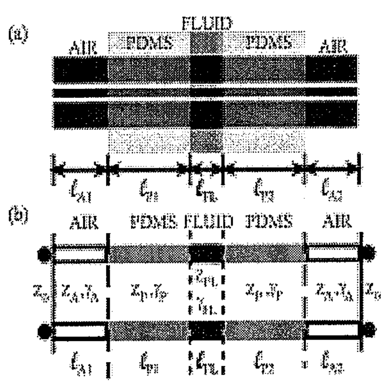

Figure 2. Schematic representation of the transmission lines loaded by the microfluidic channel. Each segment is defined by a length, and has a characteristic impedance and propagation constant that is determined by the material constituents of the transmission line segment.

Once we have de-embedded the fluid-loaded region from the overall measurement structure, we can determine the capacitance and conductance per unit length by use of an optimization routine. The capacitance and conductance per unit length of the fluid-loaded region are then related to the real and imaginary parts of the complex permittivity by means of finite-element simulations.

Results and Discussion

Figure 3 shows results for the complex permittivity of methanol over the continuous frequency range 50 MHz to 40 GHz [3]. Shown are results for CPW transmission lines of two different gaps *g* between the center conductor and ground planes, 10 μm and 20 μm. Also shown for comparison as a solid black line are data obtained by use of a shielded open-circuited technique at 20 °C, for frequencies up to 6 GHz. The agreement between the two techniques is excellent.

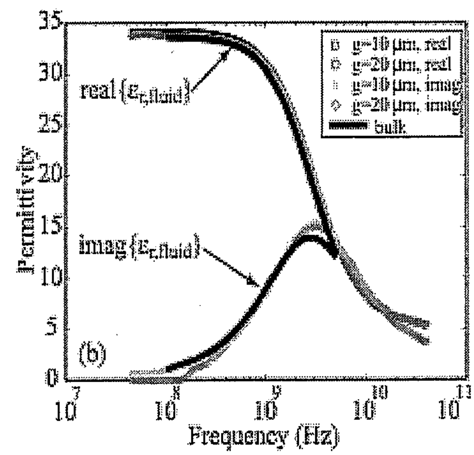

Fig. 3. Results for the frequency-dependent permittivity function of methanol at room temperature.

References

[1] J.C. Booth, J. Mateu, M. Janezic, J. Baker-Jarvis, and J.A. Beall, Broadband Permittivity Measurements of Liquid and Biological Samples using Microfluidic Channels, IEEE MTT-S International Microwave Symposium Digest, 2006, pp. 1750-1754.

[2] J. Mateu.; N. Orloff.; M. Rinehart, and J.C. Booth, Broadband Permittivity of Liquids Extracted from Transmission Line Measurements of Microfluidic Channels IEEE MTT-S International Microwave Symposium Digest, 2007, pp. 526-529.

[3] J.C. Booth, N.D. Orloff, J. Mateu, M. Janezic, M. Rinehart, and J.A. Beall, Quantitative Permittivity Measurements of Nanoliter Liquid Volumes in Microfluidic Channels to 40 GHz, to be published in IEEE Transactions on Instrumentation and Measurement.