Millimeter Wave and Terahertz Dielectric Probe Microfluidic Sensors

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Abstract— **This paper reports the design, fabrication, and characterization of a suite of dielectric probes for near-field and evanescent microfluidic sensing applications. Four different probe designs are studied. These structures are made from cylindrical alumina dielectric rods, and were integrated with microfluidic channels. Mixtures of two different solvents were used to characterize the probes. The sensitivity of the probes is measured under a continuous flow of liquids in the microfluidic channel. In comparison to evanescent wave probes, an improvement of up to 25X in sensitivity is obtained using the new probes.**

I. INTRODUCTION

Sensing of liquid samples available in small volumes is important in environmental monitoring, pharmaceutical drug discovery and quality control. Millimeter and THz waves are appealing for such sensing due to several reasons including rich spectral fingerprint in this frequency range and non-ionizing nature of radiation.

In this, paper several near field and evanescent field microfluidic sensors in the form of dielectric waveguides are presented. The key advantage of using near-field sensing lies in the ability to overcome the diffraction limit. Thus, near-field imaging can be used in probing materials and structures into sub-wavelength resolution. Pencil shaped dielectric probes made out of plastic has shown promise in the areas of near field imaging, crack detection, device probing and detection of concealed objects [1, 2]. On the other hand, evanescent sensors are best described as dielectric waveguides with field penetration into the surrounding medium. Due to the properties of the surrounding medium, the propagating and evanescent waves are affected. Hence, by monitoring the transmission through the waveguide information can be obtained about the surrounding material. Recently, a silicon waveguide has been used to monitor absorption of aqueous solutions containing different concentrations of glucose [3].

This paper improves on the designs available in the literature through the low-loss alumina dielectric waveguide based microfluidic sensor designs. Two different sets of probe designs made from alumina are studied. The probes are integrated within the microfluidic channels to further improve the sensitivity. Apart from improved sensitivity, direct integration of probes within microfluidic channels leads to reduced sample volume (down to nano-liters) and also allows in monitoring of samples under continuous flow. Here, measurements in the W-band frequency range (75GHz-110GHz) are presented.

II. DESIGN AND SIMULATIONS

Fig. 1 shows the four different probe designs made from alumina ($\varepsilon_r = 9.4$) rods with diameter of 1.56mm. The first two are evanescent wave probes (1 and 2 in Fig. 1) and the other two are near field probes (3 and 4 in Fig. 1). Probe-2 is tapered in the middle to enhance field coupling to the surrounding liquid sample. One of the near field probes has a spherical end and the other has a conical end tip. These probes were designed to fit inside the microfluidic channel. The outer ends of the probes are shallowly tapered down to a point with the vertex angle being 22^{o}. This end is coupled to the horn antennas. For the evanescent probes, the liquid is introduced in the middle section (~ 10mm length) around the waveguide. For the near field probes, the liquid is introduced in the space (~0.2mm) between the two probes.

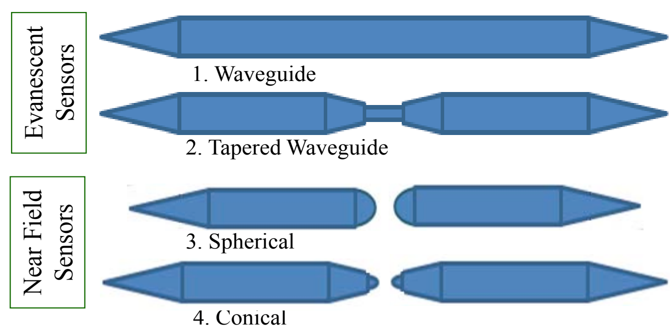

Fig. 1. Four different probe designs. Top two are evanescent probes and the bottom two are near field probes.

Ansoft HFSS was used to analyze the field surrounding or exiting the probes at the interrogation regions. Analysis was carried out at 94 GHz and assuming air ($\varepsilon_r = 1$) as the surrounding medium. Fig. 2 shows the simulated E-field distribution for the four different probes. Comparing the field distributions of evanescent sensors, the sensor tapered in the middle strongly concentrates the fields around the waveguide. High field concentration is necessary to efficiently interrogate small sample volumes. Thus, the tapered probe is expected to provide higher sensitivity. Similarly, the spherical end tip probe provides high field concentration as compared to the conical probe and is expected to provide higher sensitivity.

III. MEASUREMENT SETUP AND RESULTS

Fig. 3(1) shows the millimeter wave test setup. Here, dielectric probes are integrated within the microfluidic channels to characterize small volumes of samples in a continuous flow configuration. It consists of a W-band backward wave oscillator source (75 – 110 GHz) and a zero-bias Schottky diode detector element. Horn antennas are attached to the source and the detector. The dielectric rod (probe) passes through a microfluidic channel. The ends of the dielectric rods are partially inserted into the horn antennas and adjusted to achieve good coupling efficiency.

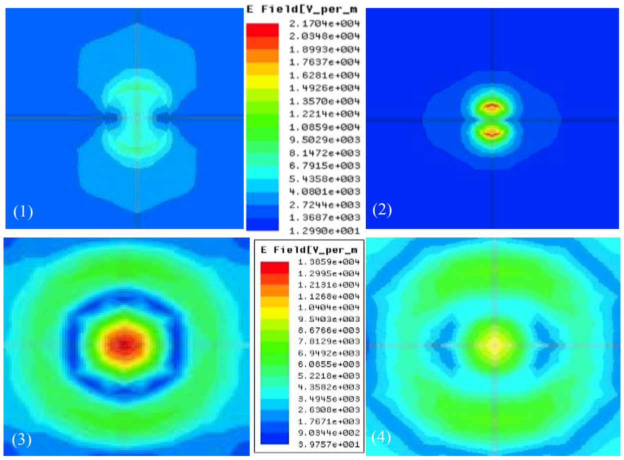

Fig. 2. E-field across the cross-section of the four probe designs: (1) Waveguide, (2) Tapered Waveguide, (3) Spherical tip, (4) Conical tip.

A microfluidic channel made from Teflon consisting of four ports is used to guide the liquid (commercially available, FIAlab Z-type fiberoptic cell). Fig. 3(2) shows the schematic diagram of the microfluidic channel. Two ports directly facing each other are used to insert the probes, and the other two ports offset from each other on the opposite ends are used for liquid flow. The inner diameter of the microfluidic channel is approximately 1.57 mm. A syringe pump is used to introduce the liquid through the microfluidic channel. The volume of liquid interrogated is less than 1μL.

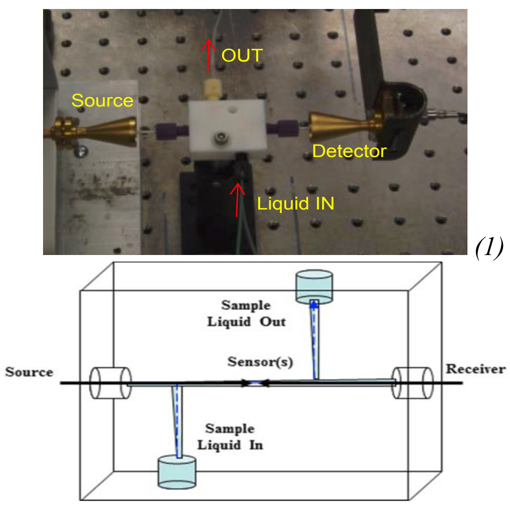

Fig. 3. (1) Test setup and (2) drawing of a sample holder.

Measurements at room temperature were carried out in transmission mode for the four probe designs using 6 different volume ratio mixtures of Cyclopentanone and Toluene solvents. Toluene and Cyclopentanone do not chemically react with each other at room temperature. Toluene is a low loss liquid (tan δ=0.0054) with a dielectric constant (ε_r) of 2.2 and Cyclopentanone is a higher loss liquid (tan δ=0.0237) with a dielectric constant (ε_r) of 2.1 [4, 5]. Thus, the liquid mixture with varying volume ratios has a relatively similar dielectric constant but varying losses. Before introducing a new sample, the previous mixture was flushed out of the capillary using Isopropyl Alcohol (IPA) and forced air. Reference measurements with IPA in the capillary were carried out for all sample mixtures. Fig. 4 shows the normalized experimental results obtained for different sensor designs.

The normalized transmitted signal increases as the percentage of cyclopenanone, lossy liquid, in the two liquid mixture decreases. This observation was true (and expected) for all the sensors. Minimum detected signal is limited by the noise floor of the Schottky diode detector. To the first order, sensitivity can be analyzed by looking at the change in signal from one extreme concentration ratio to the other. The dynamic range of detected signal of the evanescent probe is the smallest (i.e., lowest sensitivity). This is expected as the portion of the transmitted signal interrogating the sample is small as can be seen in Fig. 1. Best sensitivity is attained with a conical tip probe. The dynamic range of the probes are approximately 18dB, 15dB, 11dB and 4.5dB for conical tip, spherical tip, tapered waveguide and waveguide, respectively. This indicates that the conical tip is about 14dB (or ~25X) more sensitive than the evanescent probe. Similar results were obtained at 0.3THz, not presented here. Comparison between conical tip and spherical tip probe requires further study relative to the dielectric properties of the surrounding liquid sample while considering probe alignment measurement tolerances.

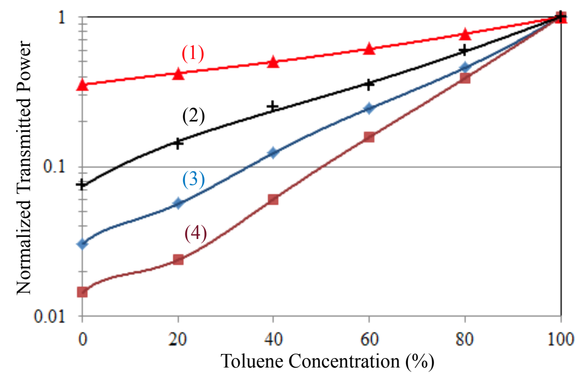

Fig. 4. Measured transmitted results of different probes with varying Toluene/Cyclopentanone solvent ratios. Probes: (1) Waveguide, (2) Tapered Waveguide, (3) Spherical tip, (4) Conical tip.

IV. SUMMARY

This paper demonstrates novel microfluidic sensors for interrogation of small volume of liquid samples in the millimeter wave. Different sets of probes are designed and co-integrated with microfluidic channels. Different well known solvent mixtures are used in the characterization of the probe designs. Details of design, fabrication and measurements will be presented in the conference.

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