Dielectric Measurement of Small Volume Liquid Samples Using Dielectric Image Guide in mm-Wave Range

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***Abstract*— A dielectric measurement method based on using dielectric image guide (DIG) is presented. This method is ideal for characterization of very small liquid samples, e.g. in the range of µl or less, and has the advantage of broadband frequency measurement. The open structure of DIG makes it very convenient to place the liquid droplet at a predetermined location.**

I. Introduction

In analysis and sensing of (bio)chemical liquid solutions, the knowledge of the dielectric properties of the sample is important particularly when the sensing technique is based on the interaction of the sample with (sub)mm-wave signal. Recently, it has been shown that the electric permittivity of DNA molecules in an aqueous solution is directly related to their binding state [1], and based upon this fact, several high sensitivity DNA sensing has been proposed in THz and sub-millimeter-wave range.

A common method for dielectric measurement of liquids is using open-ended coaxial probes, however, this technique is not accurate in high frequencies, and is not suitable for small volume samples, e.g. in the range of µl or less. To handle small size samples, resonant techniques are good choices, but the characterization is obtained in a very narrow bandwidth.

In this paper, we propose a simple method for characterization of dielectric materials based on dielectric image guide structures. The proposed method is wide band and can be used at high frequencies, and can handle small volume of samples.

II. Modeling

Fig. 1 shows the schematic of a rectangular dielectric waveguide placed on a metallic support plate to make a dielectric image guide (DIG). Dielectric waveguide has the width of 2a=2.4 mm, and height of b=1 mm, and is made of alumina. The power coupling into and out of the dielectric image guide is realized by using two metallic rectangular waveguides. At transitions, DIG is tapered to decrease the reflection.

Using a pipette, the sample droplet is placed on top surface of the dielectric. Once dispensed, the droplet spread out on the surface to fill the width of the waveguide in a certain length, and form a thin dielectric layer on top of the waveguide. Because of the liquid surface tension, it is easy to optimize the volume of the droplet such that the liquid does not overflow the side walls of the waveguide.

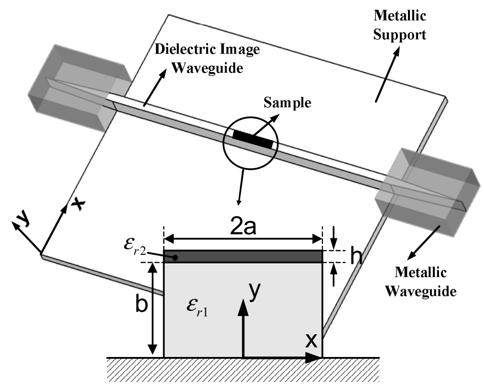

Fig. 1 Schematic of dielectric image guide structure used for dielectric measurement of small volume liquid samples along with a cross sectional view.

The thin dielectric layer of the sample, formed on top of the DIG, changes the propagation constant of the waveguide. Therefore, the phase of the transmitted signal with the sample in place differs from that of the reference measurement without the sample. Using a network analyzer, the phase of S_{21} with and without sample in place is measured in the frequency range of interest, and then the dielectric constant of the sample is extracted from the phase difference between the reference and sample measurements.

Analytical characteristic equations obtained from Marcatili's method [2] are used to calculate the propagation constant of the DIG with and without the thin dielectric layer on top. Assuming E_{11}^{y} as the dominant mode of the DIG, the characteristic equations are given as

$$k_y = \frac{1}{b}\tan^{-1}\left(\frac{\varepsilon_{r1}\alpha_{y0}}{k_y}\right) \quad (1)$$

$$k_x = \frac{1}{a}\tan^{-1}\left(\frac{\alpha_{x0}}{k_x}\right) \quad (2)$$

$$\alpha_{x0}^2 = k_0^2(\varepsilon_{r1}-1) - k_x^2 \quad (3)$$

$$\alpha_{y0}^2 = k_0^2(\varepsilon_{r1}-1) - k_y^2 \quad (4)$$

where k_x (k_y) is the transverse phase constant in x (y) direction, ε_{r1} is the relative dielectric constant of the waveguide, k_0 is the free space wave number, and $2a$ and b are the width and height of the waveguide, respectively.

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The longitudinal propagation constant, β, is obtained as

$$\beta^2 = k_0^2\varepsilon_{r1} - k_x^2 - k_y^2 \quad (5)$$

Once a thin dielectric layer of the sample is deposited on top of the waveguide, the E_{11}^y mode is perturbed in the y direction whereas it is almost kept unchanged in the x direction. Therefore, in this case, k_x can be obtained from (2) and (3), and the modified transverse phase constant in y direction, k'_y, can be extracted from the following transcendental equation [2].

$$\frac{\varepsilon_{r2}k'_y}{\varepsilon_{r1}k_{y2}}\tan(k_{y2}h)\tan(k'_y b) + \frac{1}{\alpha_{y0}}\left[\frac{k_{y2}}{\varepsilon_{r2}}\tan(k_{y2}h) + \frac{k'_y}{\varepsilon_{r1}}\tan(k'_y b)\right] = 1 \quad (6)$$

$$\alpha_{y0}^2 = k_0^2(\varepsilon_{r1} - 1) - k_y'^2 \quad (7)$$

$$k_{y2}^2 = k_0^2(\varepsilon_{r2} - \varepsilon_{r1}) - k_y'^2 \quad (8)$$

where h is the thickness of the thin layer sample, and ε_{r2} is the relative dielectric constant of the thin layer sample. The longitudinal propagation constant with the thin layer on top, β', is obtained as

$$\beta'^2 = k_0^2\varepsilon_{r1} - k_x^2 - k_y'^2 \quad (9)$$

The phase difference in the transmission response, S_{21}, of the DIG with and without the sample in place is determined as

$$\Delta\Phi = (\beta' - \beta)L \quad (10)$$

where L is the length of the sample layer formed on top of the waveguide.

Finding the dielectric constant of the thin layer sample, ε_{r2}, from the measured phase difference, $\Delta\Phi$, can be treated as an inverse problem; knowing the measured phase difference, $\Delta\Phi$, in the frequency range of interest, the modified longitudinal propagation constant, β', can be obtained from (10). Then, the modified transverse phase constant in y direction, k'_y, is determined using (9). Finally, the dielectric constant of the thin layer sample, ε_{r2}, is solved from the transcendental equation given by (6).

Applying the aforementioned method, Fig. 2 shows the measured dielectric constant for 1 µl droplet of water. The measurement result is in a very good agreement with those reported in the literature using other techniques [3].

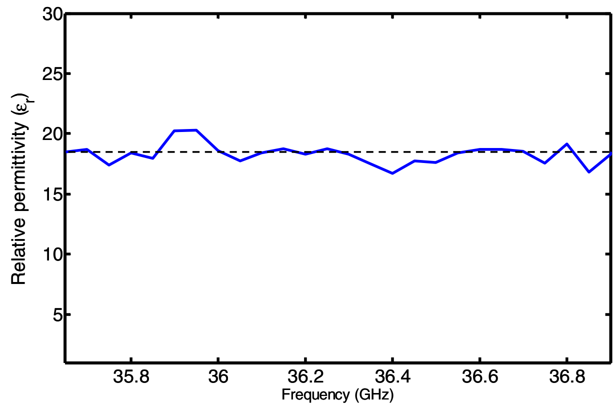

Fig. 2 Measured electric permittivity (real part) of 1 µl water droplet. ε_r is measured around 18.2.

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