Permittivity and Dielectric Loss Measurement of Paraffin Films for mmW and THz Applications

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Abstract—Complex permittivity measurement of thick paraffin films at the frequency range of 0.3 THz – 1 THz is presented. Paraffin is a low loss dielectric that undergoes reversible volumetric mechanical phase change. These unique properties of the paraffin can be employed to develop reconfigurable antenna systems and RF components at millimeter wave (mmW) and terahertz (THz) bands. In order to characterize the dielectric properties of the paraffin, terahertz time domain spectroscopy is used. Complex dielectric permittivity is modeled using Havriliak-Negami relaxation and measured data are fitted using three-layer propagation model. Measured loss tangent for various paraffin films is in the range of $0.3 \times 10^{-3} – 7.7 \times 10^{-3}$ and the relative permittivity is found to be 2.26.

Keywords—Loss tangent, millimeter-wave (mmW), paraffin, permittivity, terahertz, time-domain spectroscopy.

I. INTRODUCTION

Paraffin is a phase-change material that exhibits approximately 15% volumetric change at relatively low temperature (75°C). Also, this material exhibits low dielectric loss at mmW and THz frequencies. These unique features of paraffin can be used to develop reconfigurable antennas and RF components. To employ these capabilities, complex permittivity characterization of the paraffin is needed.

An earlier study on the dielectric loss mechanism of paraffin is reported by Jackson where loss tangent of the paraffin is measured using parallel plate condensers [1]. According to this study, loss tangent of the paraffin over the frequency range of 1.8 MHz - 14.2 MHz is less than $5 \times 10^{-3}$. Manzari et al. characterized the paraffin using a commercial network analyzer at the frequency range of 800 MHz - 1 GHz and the relative dielectric constant and loss tangent is reported as 2.1 and $9.8 \times 10^{-4}$, respectively [2].

In the previous studies paraffin is characterized at lower frequencies. However, these measurement techniques are not suitable for mmW and THz frequencies. Resonator-based techniques are inherently narrow band and measurements are only valid around the resonance frequency. In waveguide-based measurements, conductor loss and radiation are dominant loss mechanisms. Consequently, this method does not have sufficient sensitivity for low-loss dielectric materials. Unlike waveguide-based and resonator-based methods, free-space technique offers accurate calculation of dielectric loss over a wide frequency range. In this study we use a free space measurement technique using THz time-domain spectroscopy (TDS) to calculate the complex dielectric permittivity. Similar measurement procedure was previously reported for SU-8 films [3].

In the following section, measurement setup and the analytical model that is used to extract complex dielectric permittivity is described. In Section III, measurement results for various thickness of paraffin films are given. Discussion of the results and inaccuracies are given in Section IV.

II. MEASUREMENT SETUP AND ANALYTICAL MODEL

For the measurement, four paraffin samples with thickness of 0.5 mm to 1.6 mm are fabricated. Using a commercial THz TDS system (TPS Spectra 3000 from TeraView Ltd), transmittance and the phase of the transmitted wave through the samples are measured. Measurement environment is purged with N₂ to remove the effects of the O₂ and water vapor absorption. Measurements are performed in the range of 60 GHz – 3 THz with a frequency resolution of 734 MHz. For the analysis, measured data in the range of 300 GHz – 1 THz that have acceptable signal-to-noise ratio are used.

THz TDS system is a free space measurement technique and complex dielectric constant of the sample can be measured using the phase and amplitude of the transmitted pulsed wave. Considering a normal incident plane wave and isotropic homogeneous medium, transmission coefficient through a paraffin slab can be found as [4],

\[
T = \frac{4k_0k_d\exp(-j(k_d - k_0)d)}{(k_0 + k_d)^2 - (k_d - k_0)^2\exp(-2jk_d d)}
\] (1)

where $k_d$ and $k_0$ are wavenumbers in paraffin and free space, respectively. $d$ denotes the thickness of the sample. Note that in this model, all the reflection and transmissions form the boundaries are considered and $T$ is the total transmission coefficient. In Eq. (1), $k_d$ is a complex number which is related to the unknown complex permittivity as $k_d = \omega \sqrt{\mu_0 \epsilon_r}$. Relative dielectric constant of the paraffin is modeled using Havriliak-Negami relation [5] as,

\[
\epsilon_r = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{(1 + (j\omega\tau)^{1-\alpha})^\beta}
\] (2)

Unknown parameters in Eq. (2) ($\epsilon_s, \epsilon_\infty, \tau, \alpha$ and $\beta$) as well as the thickness of the sample, $d$, are determined using an iterative non-linear least-squares optimization by fitting the measured transmittance data to the analytical transmission coefficient. Note that both phase and the amplitude measurements are used in the optimization.
III. EXPERIMENTAL RESULTS

Thickness of the four samples are measured using a micrometer with a resolution of 0.4 µm and the measured values are used as the initial estimate in the iterative optimization. Thickness of the samples are, 0.5 mm, 0.8 mm, 1.2 mm and 1.6 mm. Unknown parameters for these samples are determined by comparing the measured transmission coefficient and the analytical model. Fig.1 shows the amplitude and phase of the transmittance with respect to frequency for the 0.8 mm-thick sample. According to Fig. 1, experimental results and the model are in good agreement and thickness of this sample is estimated as 0.698 mm. Loss tangent (defined as, \( \tan \delta = \frac{\text{Im}(\varepsilon_r)}{\text{Re}(\varepsilon_r)} \)) and the real part of the permittivity are plotted in Fig. 2 and Fig. 3, respectively. Relative dielectric constant (\( \varepsilon_r \)) is calculated to be 2.248 – 2.283 for all samples and it is found to be approximately constant for entire frequency band. Measured loss tangent is ranging from 0.3 \( \times \) 10\(^{-3} \) to 7.7 \( \times \) 10\(^{-3} \) for various thicknesses. In addition, loss tangent is increasing with respect to frequency which is consistent with the previous study performed on n-Alkanes [6].

IV. DISCUSSION

A systematic approach to measure the complex dielectric constant of the thick paraffin films over the wide frequency range of 0.3 THz – 1 THz was presented. Transmitted wave through paraffin films are measured using time-domain spectroscopy and an analytical model is used to accurately extract the complex permittivity. Using this procedure, very low values for the loss tangent is measured. Real part of the permittivity is approximately constant over the wide frequency range of 0.3 THz – 1 THz for different samples. Low loss characteristic of paraffin, makes it an attractive material for the fabrication of mmW and THz components and antennas.

Even though, measurements results for real part of the permittivity is consistent for different thicknesses, loss tangent calculations have some limitations. Measured loss tangent values vary for different samples. Non-planar surface of the samples and its roughness could contribute to the errors. Another possible source of error is oblique incident angle. To improve these preliminary results, more samples with uniform thickness will be measured. Furthermore, in order to avoid local minimas in the optimization scheme, transmittance and reflectance values will be simultaneously included in our model.

REFERENCES


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