Progress In Electromagnetics Research, PIER 42, 131–142, 2003

MEASUREMENT OF COMPLEX PERMITTIVITY OF LIQUIDS USING WAVEGUIDE TECHNIQUES

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Abstract—Complex permittivity of a number of liquids and binary mixtures has been studied by measurement using the waveguide techniques at the X and Ku band. Particular pieces of WR90 and WR62 waveguides were designed for the measurement of liquid materials. The custom designed TRL calibration kits are applied for calibration of the waveguide system. The measured results of complex permittivity of liquid dielectrics, such as methanol, propyl alcohol, ethyl alcohol, chlorobenzene, dioxane, cyclohexane and binary mixtures, are presented. Particular pieces of open-ended waveguides for the X and Ku bands were also designed for holding liquids and the measured data using the open-ended waveguide technique were compared with those measured using the waveguide technique. Some of the measured results are also compared with calculated data using the Debye equation and published data measured by the Fourier transform spectroscopy.

1. INTRODUCTION

Accurate determination of complex permittivity data of liquid materials at microwave frequencies are necessary for applications such as the evaluation of biological effects in biological molecules and in solvents. Alcohols or other liquid dielectrics can be considered as good solvent materials for a number of biological molecules, body tissues, blood and bone marrow. Therefore, a thorough permittivity study of various common solvents is essential for biomedical research. A number of techniques has been developed which have the potential to be applied for the measurement of complex permittivity of liquids such as the waveguide technique [1–4], the open-ended waveguide technique [5, 6], open-ended coaxial line technique [7, 8], dispersive Fourier transform spectroscopy (DFTS) [9, 10] and microwave resonant method [11].

The waveguide technique and open-ended waveguide technique are accurate for the measurement of complex permittivity. These nondestructive techniques are based on the reflection coefficient and transmission coefficient measurement from which the dielectric or magnetic properties of materials can be determined. In addition, these technique are well suited for the measurement of liquid solvent materials. However, for the measurement of liquid materials, the key problem is how to hold the liquid inside the waveguide for the waveguide technique and outside the waveguide for the open-ended waveguide technique.

In this paper, we employ the waveguide techniques for measuring liquid dielectrics due to their high accuracy. Particular pieces of liquid holder for WR90 and WR62 waveguides are designed for the measurement of liquid materials. The complex permittivity of a number of liquid solvents has been investigated experimentally using the designed liquid holders at the X and Ku band. Particular pieces of open-ended waveguides for the X and Ku bands are also designed for holding liquids. The measured data using the waveguide technique is compared with those measured using the open-ended waveguide technique and with those from the literature.

2. ANALYSIS

2.1. Waveguide Technique

Fig. 1 shows the designed liquid holder and the measurement setup for the waveguide technique. The liquid holder consists of WR62 or WR90 waveguide with a shallow pocket at both openings. This allows for a thin sheet of Kapton polyamide film to be placed in the shallow pocket and sealed with an epoxy adhesive. Threaded access holes are placed

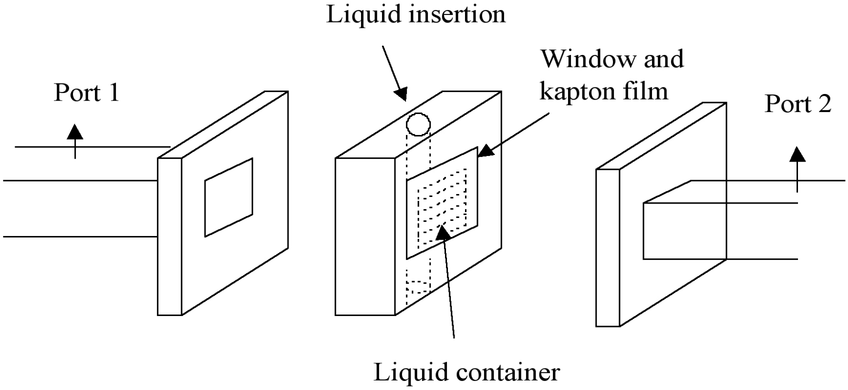

Figure 1. Designed liquid holder and measurement setup for the waveguide technique.

at the top and bottom of the holder to be used to inject and remove the test liquid. These holes are then secured from liquid leakage using sealing screws.

By the transmission line theory, the transmission coefficient S_{21} can be expressed by $S_{21} = \frac{4\Gamma_1\Gamma_0}{(\Gamma_1+\Gamma_0)^2 e^{\Gamma_1 L} - (\Gamma_1-\Gamma_0)^2 e^{-\Gamma_1 L}}$, where $\Gamma_0 = j\beta_0$ and $\Gamma_1 = \alpha_1 + j\beta_1$. Here the propagation coefficient of air filled waveguide $\beta_0 = \frac{2\pi}{\lambda_0}\left[1 - (\frac{\lambda_0}{\lambda_c})^2\right]^{1/2}$, the propagation coefficient of loaded waveguide $\alpha_1 + j\beta_1 = \frac{2\pi}{\lambda_0}\left[(\frac{\lambda_0}{\lambda_c})^2 - \varepsilon_r\right]^{1/2}$, λ_0 and λ_c are the wavelength of free space and the cutoff wavelength of the waveguide for TE_{10} mode, and $\varepsilon_r = \varepsilon' - j\varepsilon''$ is the relative complex dielectric constant. The S_{21} is a function of complex permittivity of the specimen, therefore, once the measured transmission coefficient S_{21} are obtained, the complex permittivity of the specimen can be extracted by an optimization procedure such as the Newton-Raphson method.

2.2. Open-Ended Waveguide Technique

For comparison purpose, the open-ended waveguide technique was also developed following the procedures presented in [5]. However, the common used open-ended flange is flat, so it is difficult to hold liquids. In this work, two rectangular flanges with stepped walls for WR90 and WR62 waveguides, respectively, were designed for holding liquid materials. Fig. 2 shows the stepped flange designed for open-ended waveguide technique. The aperture size of the liquid holders

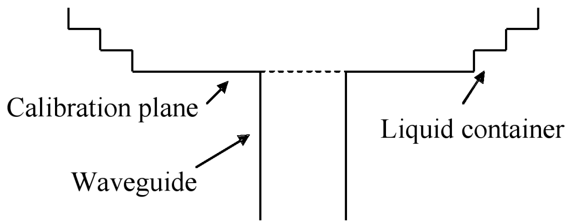

Figure 2. The stepped flange designed for open-ended waveguide technique.

is 150 mm×150 mm and the depth of each stepped wall is 5mm. The stepped walls were designed for the liquid holders so that the liquid samples can be measured at different thickness. The technique is based on the reflection coefficient S_{11} measurement from which the dielectric properties of materials can be determined. The reflection coefficient from the open-ended waveguide can be calculated by various methods. In this paper, the reflection coefficient is derived by solving the boundary value problem using a Rayleigh-Ritz technique, following the procedures presented in [5]. The reflection coefficient of a slab-like sample backed by a conducting plate can be expressed by $S_{11} = \frac{1-y}{1+y}$, where $y = \frac{jab}{2k_1D^2}\int_{S'}\int_S f(x,y)f(x',y')G(x,y;x',y')dxdydx'dy'$, $D = \int_s f(x,y)\sin\frac{\pi x}{a}dxdy$, $k_1 = \sqrt{(\frac{2\pi}{\lambda})^2 - (\frac{\pi}{a})^2}$, a and b are the dimensions of the rectangular waveguide, λ is the wavelength in free space, $G(x,y;x',y')$ is the Green function valid in the dielectric medium outside of the waveguide which implicitly contains the permittivity of the liquid, S or S' is the area of the waveguide aperture, and $f(x,y)$ is the trial function in the waveguide aperture plane which can be expanded over the completed set of the orthonormal waveguide modes. The complex permittivity of the sample can be determined by minimizing the difference between the calculated and measured reflection coefficients.

3. MEASUREMENT

The waveguide system is connected with Agilent 8510C Vector Network Analyzer for measuring the S-parameters. To calibrate the waveguide system, a few calibration techniques can be employed that include three-reference standards, waveguide calibration kits or thru-reflect-line (TRL) calibration kits. The procedure using three-reference standards works as follows. First, following the one port S_{11} calibration procedure of open-short-load, calibrate the coaxial line that connects the network analyzer and the coax-to-waveguide adapter. Then, calibrate the waveguide using three references such as a matched load and two offset short circuits or a sliding short circuit [6]. A waveguide calibration kit is normally composed of two offset short circuits with known depths and a matched load. These calibration circuits are connected to the waveguide following the procedures of the calibration, respectively, and the calibrated results are sound. The waveguide calibration kit can be custom designed using VNA Cal Kit Manager. The TRL calibration technique is applied for the work described in this paper because it is the most promising method. The TRL calibration kit is custom designed using VNA Cal Kit Manager. The kit simply consists of a short circuit and a waveguide line section with a known length. The line section length should not be greater than half a waveguide wavelength. It is chosen to be a quarter nominal waveguide wavelength $\lambda_{gn} = \frac{2(\lambda_{gl} \times \lambda_{gh})}{(\lambda_{gl} + \lambda_{gh})}$, where λ_{gl} and λ_{gh} are wavelengths of the low frequency end and the high frequency end at the corresponding frequency band, respectively. The accuracy of these standards is excellent because it is not difficult to make an accurate short circuit and a quality piece of waveguide in terms of its accuracy of characteristic impedance. A thru, a short for each port and a delay line were applied but the isolation was omitted in this measurement.

After the TRL calibration is performed on the waveguide ports, for the thru case, it was observed that the amplitude variation of S_{21} is less than $-0.01\,\mathrm{dB}$ and the phase is less than $200\,\mathrm{m}^\circ$ for both the X-band and Ku band. The effect of the designed liquid holder (air filled) on the S_{21} was studied by comparing the S_{21} measured using a same length waveguide (air filled). It was observed that the decay and phase shift due to the particular design is less than $-0.1\,\mathrm{dB}$ and less than 3°, respectively. The decay and phase shift are attributed from the thin dielectric sheet sealing both waveguide openings of the liquid holder.

4. MEASURED RESULTS

The measurements were carried out at the X and Ku-band at room temperature 23°C. Fig. 3 shows the measured permittivity of ethyl alcohol at the X-band using the waveguide technique. Two types of holders were used, the designed liquid holder and a piece of waveguide that is sealed with Scotch tape. It is seen that the measured results using the designed liquid holder agree reasonably well with those measured using a piece of waveguide containing the liquid sample sealed by the Scotch tape. However, the designed liquid holder is

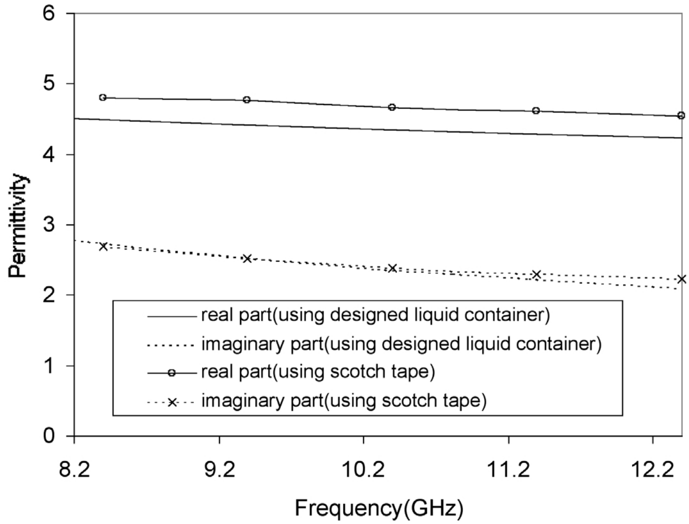

Figure 3. Permittivity of ethyl alcohol measured using the designed waveguide liquid holder and Scotch tape at the X-band.

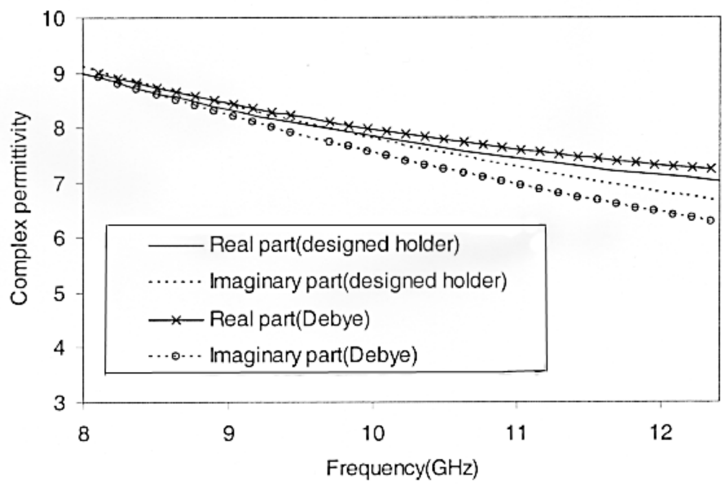

Figure 4. Permittivity of methanol measured using the designed waveguide liquid holder and calculated by the Debye equation at the X-band.

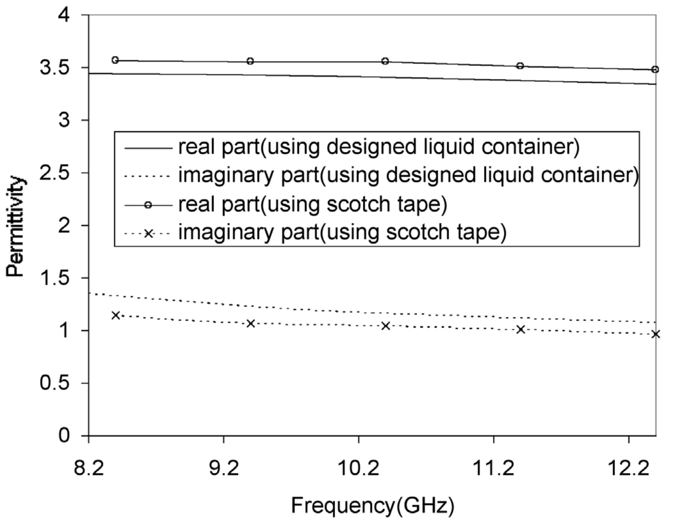

Figure 5. Permittivity of propyl alcohol measured using the designed waveguide liquid holder and Scotch tape at the X-band.

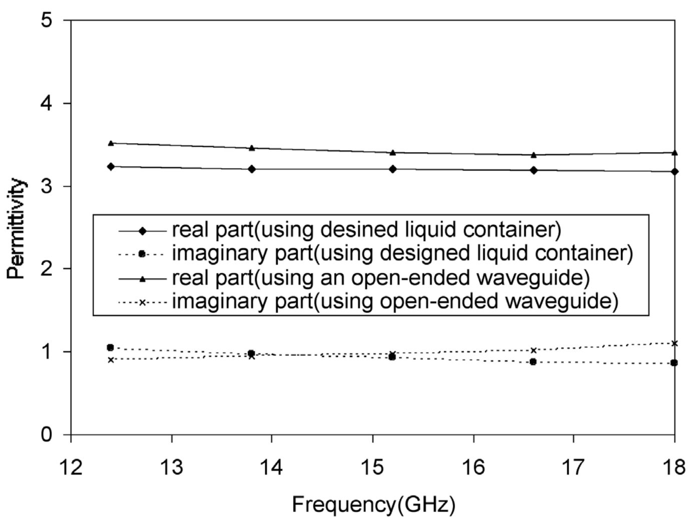

Figure 6. Permittivity of propyl alcohol measured using the designed waveguide liquid holder and the designed stepped flange for open-ended waveguide technique at the Ku-band.

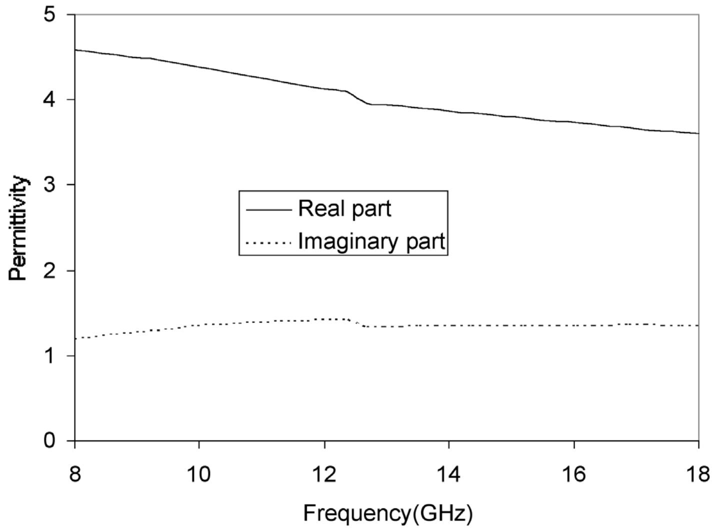

Figure 7. Permittivity of chlorobenzene measured using the designed waveguide liquid holder at the X- and Ku-band.

more stable and convenient than the Scotch tape because the liquids may resolve the Scotch tape and this makes the Scotch tape unstuck. Fig. 4 shows the complex permittivity of methanol measured using the designed waveguide liquid holder at the X-band. It is seen that the measured result agrees quite well with the calculated data using the Debye equation [7]. Fig. 5 shows the measured permittivity of propyl alcohol at the X-band together with the data measured using the Scotch tape.

Fig. 6 shows the measured permittivity of propyl alcohol at the Ku-band by using the designed waveguide liquid holder, compared with the measured data using the designed stepped flange for the open-ended waveguide technique. It is seen that the measured results by the waveguide technique agree well with those measured using the open-ended waveguide technique. It is also observed that the permittivity of propyl alcohol at the overlapping frequency 12.4 GHz measured at the Ku-band agrees well with that measured at the X-band. It should be mentioned by our experimental experience that the designed waveguide sample holders for the waveguide technique are easier to handle and more reliable than the designed stepped flanges for the open-ended waveguide technique. It is sometimes difficult to extract the complex permittivity for the open-ended waveguide technique because the open-

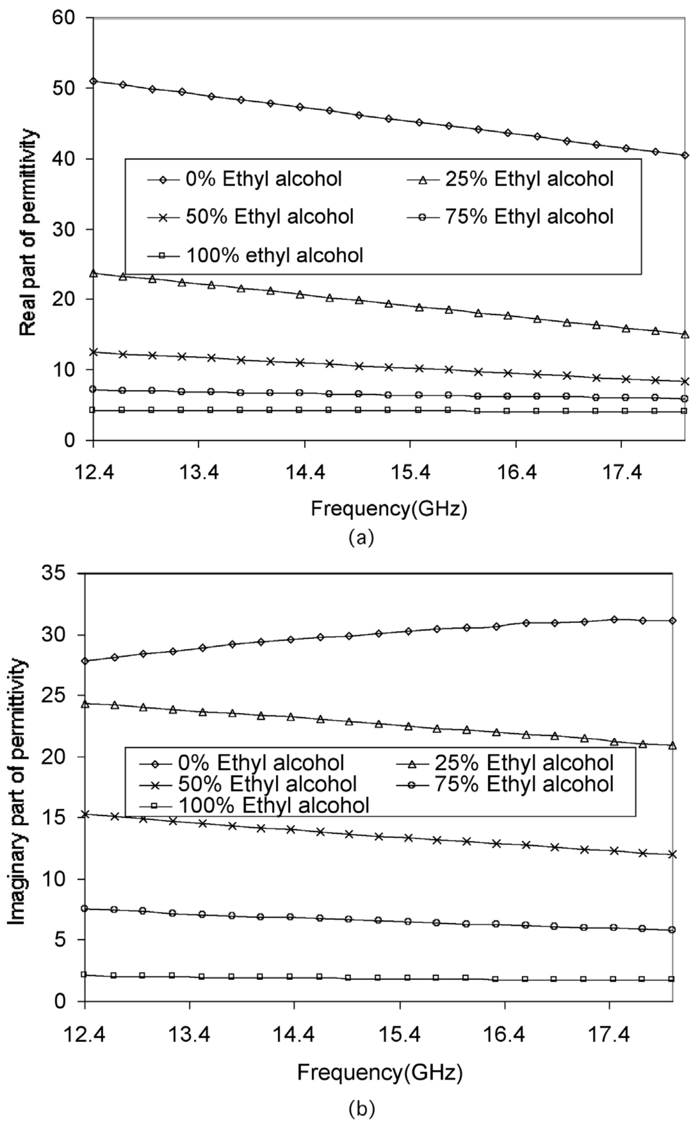

Figure 8. Complex permittivity of binary mixture of ethyl alcohol and water measured using the designed waveguide liquid holder at the Ku-band (a) real part (b) imaginary part.

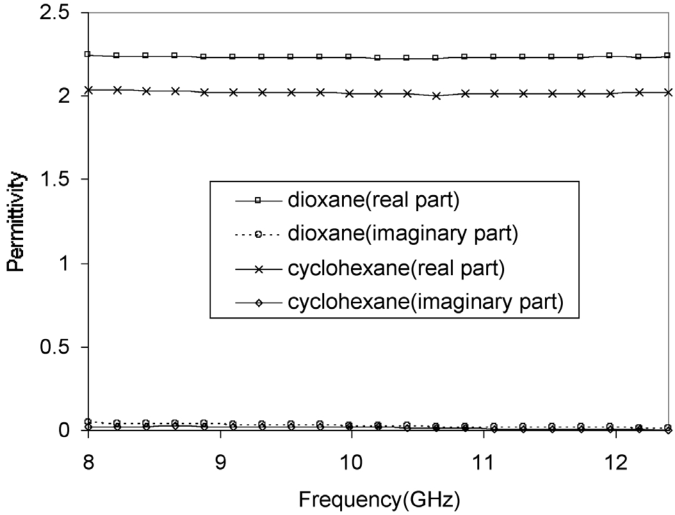

Figure 9. Permittivity of dioxane and cyclohexane measured using the designed waveguide liquid holder at the X-band.

ended waveguide technique is more sensitive to the experimental errors than the waveguide technique. It is noted that the complex permittivity is extracted from the reflection coefficient S_{11} for the open-ended waveguide technique while the complex permittivity is extracted from the transmission coefficient S_{21} for the waveguide technique. The S_{11} is generally more difficult to be accurately measured than the S_{21}.

Fig. 7 shows the measured permittivity of chlorobenzene at the X- and Ku-band using the designed waveguide liquid holder. It is seen that the continuity between the two bands is quite good. The result agrees with that measured by the dispersive Fourier transform spectrometry in a higher frequency range. For example, the dielectric constant of chlorobenzene is approximately 3.61 at 15 GHz [9]. Fig. 8(a) and Fig. 8(b) show the measured real part and imaginary part of complex permittivity of binary mixture of ethyl alcohol and distilled water at the Ku-band, respectively. The difference of complex permittivity due to the various percentages of the binary mixture is clearly shown, and this is expected to be used for identifying the contents of binary mixtures. Finally, Fig. 9 shows the complex permittivity of two low loss liquids, dioxane and cyclohexane, measured using the designed waveguide liquid holder at the X-band. This result is consistent with that measured at higher frequencies [10], demonstrating that the waveguide technique is equally effective for low loss liquids.

5. CONCLUSION

Complex permittivity of a number of liquid dielectrics such as methanol, propyl alcohol, ethyl alcohol, chlorobenzene, dioxane, cyclohexane and binary mixtures, have been measured using the waveguide techniques at the X and Ku band. The custom designed TRL calibration kits are applied for the calibration of the waveguide system. Particular pieces of waveguides for both the waveguide technique and open-ended waveguide technique were designed for holding the liquids. The measurement of complex permittivity for the liquids manifested the dielectric properties of the liquid materials. This work demonstrates that the designed liquid holders are effective for the measurement of complex permittivity of low loss, medium loss and lossy liquids. The research work conducted in this paper is expected for microwave biomedical applications.

ACKNOWLEDGMENT

The authors would like to thank Anthony N. Andreucci for design of the waveguide sample holder and Rene Grignon for his assistance in the measurement.

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