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4. The Dielectric Constant of Liquids at Microwave Frequencies. (II)

Measurements of the Dielectric Constant at 3 cm Wavelength

Naokazu Koizumi

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The method of measurement of the complex dielectric constant \((\varepsilon^* = \varepsilon' - j\varepsilon'')\) at 3 cm wavelength with the waveguide apparatus was discussed and some measurements were made on aliphatic alcohols.

The block diagram of the test apparatus is shown in the figure. The details about waveguide components have been already reported (This Bulletin, 28, 55 (1952)).
For the medium and high dielectric loss liquid, the propagation constant $\tau_d$ in the dielectric-filled section of waveguide may be expressed as

$$\tau_d = \alpha_d + j \frac{2\pi}{\lambda_d}$$

$$= j \frac{2\pi}{\lambda_o} \left( \frac{\lambda}{\lambda_o} \right)^{\frac{1}{2}} \left( \frac{\lambda}{\lambda_o} \right)^{\frac{1}{2}} - \frac{1}{2}$$

where $\lambda_o$ is the wavelength in free space, $\lambda_d$ the cut-off wavelength in the empty guide, $\lambda$ the wavelength in the dielectric-filled waveguide and $\alpha_d$ the attenuation constant due to the dielectric loss of liquid.

From the above relation $\lambda_d$ and $\alpha_d$ are written in the form

$$\lambda_d = \frac{\lambda_o}{\epsilon - \epsilon' - \epsilon'' - \left( \frac{\lambda_o}{\lambda} \right)^{\frac{1}{2}} - \frac{1}{2}}$$

$$\alpha_d = \frac{\pi \epsilon'' \lambda_d}{\lambda_o^2}$$

Then the real and imaginary parts of dielectric constant are given by the equations

$$\epsilon' = \left( \frac{\lambda_o}{\lambda} \right)^{\frac{1}{2}} + \left( \frac{\lambda_o}{\lambda} \right)^{\frac{1}{2}} - 1 - \left( \frac{\alpha_d \lambda_d}{2\pi} \right)^2$$

$$\epsilon'' = \frac{1}{\pi} \left( \frac{\lambda_o}{\lambda} \right)^{\frac{1}{2}} \alpha_d \lambda_d$$

Hence, the procedure for calculating $\epsilon'$ and $\epsilon''$ is to measure $\lambda_d$ and $\alpha_d$ in the liquid after determining $\lambda_o$ and $\lambda$ characteristic of the apparatus.

For a constant incident power, the amplitude of the reflected wave may be proportional to the magnitude of reflection coefficient, $|l'|$, at the face of the dielectric sample. The latter will be given by the following equation, when the sample is terminated by an ideal open-circuited plunger,

$$l' = \left| \frac{Z_d \coth \tau l - 1}{Z_d \coth \tau_d l + 1} \right|$$

where $l$ is the length of liquid column, and $Z_d$ is the per unit characteristic impedance in the liquid-filled waveguide. For the TE mode $Z_d$ is related to the dielectric constant and the wavelengths, $\lambda$, and $\lambda_d$, by the equations

$$Z_d = \frac{\left[ 1 - \left( \frac{\lambda_o}{\lambda} \right)^{\frac{1}{2}} \right]}{\epsilon - j \epsilon' - \left( \frac{\lambda_o}{\lambda} \right)^{\frac{1}{2}} - \frac{1}{2}} \approx Z_{d2} \epsilon^j \lambda_d$$

$$Z_{d2} = \frac{1 - \left( \frac{\lambda_o}{\lambda} \right)^{\frac{1}{2}}}{\epsilon' - \left( \frac{\lambda_o}{\lambda} \right)^{\frac{1}{2}}} \times \left[ 1 + \left( \frac{\epsilon'}{\epsilon'' - \left( \frac{\lambda_o}{\lambda} \right)^{\frac{1}{2}}} \right)^{\frac{1}{2}} \right]$$

$$\phi_d = \frac{1}{2} \tan^{-1} \left( \frac{\epsilon''}{\epsilon' - \left( \frac{\lambda_o}{\lambda} \right)^{\frac{1}{2}}} \right)$$
Since the output reading of a crystal detector coupled to the reflected wave by the directional coupler is proportional to $|I|^2$, for the lengths of the liquid which are odd integral multiples of $\lambda_d/4$, the set of values of the output reading i.e. $|I|^2$ may be written in the form.

$$
|I|^2_n = \frac{1-Z_d^2}{1+Z_d^2} + 2\frac{1-Z_d^2}{1+Z_d^2} \exp \left(-n\alpha_d\lambda_d/2\right) + \exp \left(-n\alpha_d\lambda_d\right)
$$

$$
I = n\cdot\lambda_d/4, \ n = 1, 3, 5, \ldots
$$

For the large values of $n$ and $\alpha_d$, the above equation reduces to

$$
\left|\frac{I}{I_n}\right|^2 = 1+2\frac{1-Z_d^2}{1+Z_d^2} \exp \left(-n\alpha_d\lambda_d/2\right),
$$

where

$$
\left|\frac{I}{I_n}\right|^2 = \frac{1-Z_d^2}{1+Z_d^2}.
$$

Therefore, the dielectric attenuation per wavelength $\alpha_d \lambda_d$ is evaluated from the slope of $\ln \left(\left|\frac{I}{I_n}\right|^2/\left|\frac{I}{I_0}\right|^2\right) - 1$ plotted against $n$.

Since $\lambda_d$ is twice the separation between adjacent maxima of the output reading, the complex dielectric constant will be calculated from the equations (1) and (2).

The observed data on five aliphatic alcohols are shown in the following table.

| Dielectric Properties of aliphatic alcohols at $\lambda_0 = 3.03\text{cm}$ |
|---------------------------------|----------|----------|----------|----------|
|                                | n-Propanol | iso-Propanol | n-Butanol | iso-Butanol | iso-Pentanol |
| $\lambda_d \text{ cm}$         | 1.74      | 1.69      | 1.83      | 1.92      | 1.96        |
| $\alpha_d \lambda_d$          | 1.146     | 1.24      | 0.849     | 0.800     | 0.663       |
| $\varepsilon (20^\circ)$      | 3.36      | 3.52      | 3.13      | 2.88      | 2.90        |
| $\varepsilon'' (\nu)$         | 1.11      | 1.27      | 0.741     | 0.634     | 0.523       |
| $\tan \delta (\nu)$           | 0.33      | 0.36      | 0.24      | 0.22      | 0.18        |

5. X-Ray Study on Thallium Foils

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The crystal structure of thallium changes from the close-packed hexagonal (low temp. phase) into the face-centered cubic (high temp. phase) at about 231°C.

On cobalt, having the same structural relation as Tl, it has been studied by U. Dehlinger, Z. Nishiyama, A. R. Troiano, et al. that its high temp. Phase