THERMAL-WAVE RESONATOR CAVITY: MODELING AND APPLICATIONS FOR WATER MIXTURES

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Summary A novel technique for ultra-high resolution measurements of the thermal diffusivity of liquid mixtures in a Thermal-Wave Resonator Cavity was developed. This device is very sensitive to thermal diffusivity variations of the intracavity sample by virtue of the exponential dependency of the signal on this quantity. Frequency scan experiments were performed. A theoretical model describing the one-dimensional temperature field within the cavity was developed. Comparison between the theoretical and experimental data (signal amplitude and phase) shows good agreement. To achieve ultra-high sensitivity of the measurements we applied a novel signal baseline suppression technique known as "Common-Mode Rejection Demodulation."

BACKGROUND

In recent years, photothermal techniques have been successfully employed for precise and accurate measurements of thermal properties of aqueous solutions. In this work we developed a photothermal technique for ultra-high resolution measurements of thermal diffusivity of liquid mixtures, namely water-alcohol solutions using a Thermal-Wave Resonator Cavity (TWRC), [1] Fig. 1. One cavity wall is made of metal (aluminum) film. The other wall is the surface of a pyroelectric polyvinylidene fluoride (PVDF) sensor.

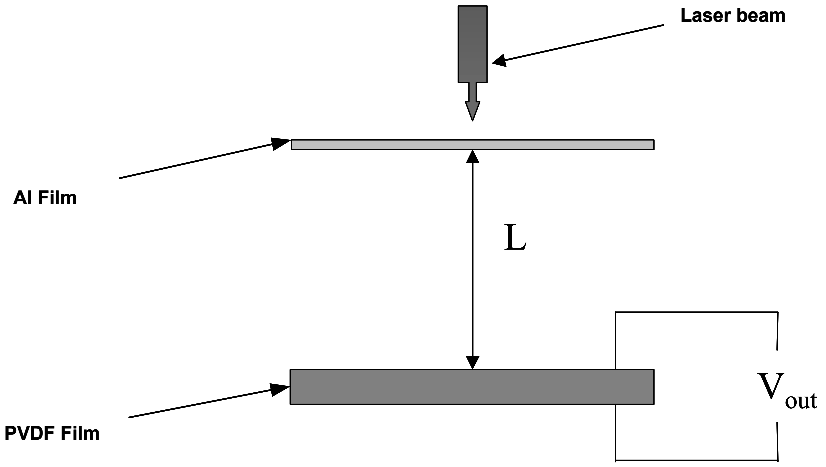

Fig.1. Thermal-Wave Resonator Cavity

The aluminum foil surface exterior to the cavity is slightly sooted to eliminate light reflection and enhance optical absorption and thermal-wave generation from a modulated laser beam. The generated thermal wave field causes temperature oscillations inside the cavity. The PVDF sensor detects the thermal wave launched by the optically heated foil and produces an electrical signal.

The conventional thermal-wave cavity method is very simple and inexpensive. Its high sensitivity to the thermal diffusivity of the intracavity material is due to the exponential dependency of the signal on the thermal diffusivity of the intracavity sample as a function of modulation frequency. However, resolution of minute diffusivity variations is limited by signal baseline (dynamic range). To achieve ultra-high diffusivity resolution in measurements at low concentrations of liquids with water mixtures we applied to the TWRC method the common-mode rejection demodulation (CMRD) scheme.[2]

The CMRD technique involves the launching of two pulses over one modulation period (Fig. 2). In this case, LIA output is the difference between the response waves produced by each one of the two pulses**.** This differential technique improves the limitations of the conventional single square-wave modulation through its ability to suppress the background LIA signal baseline, even in the presence of a strong input signal.[2] Thus, the CMRD increases considerably the dynamic range of the measurement system beyond typical dynamic ranges of modern LIAs and detects small signal variations induced by minute difference in the thermal diffusivity of the intracavity fluid.

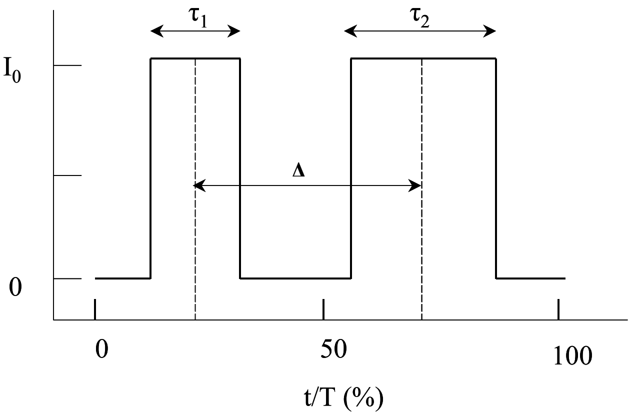

Fig.2. Optical excitation waveform consists of a bimodal pulse applied to TWRC. The horizontal time units are expressed as a percentage of a full repetition period T, τ_1 and τ_2 are the corresponding square pulse width and Δ is center-to-center time delay.

RESULTS

An experimental TWRC set-up was designed for the measurements of thermal diffusivity of liquids. The design involves fixed dimensions of the cavity length at a fixed modulation frequency and a scanned CMRD waveform pulse for obtaining reproducible measurements with various types of water-liquid solutions. Frequency scan experiments with liquid samples were performed. We also found, that accuracy of the measurements is considerably affected by the flatness of the aluminum film (Fig.1). A preliminary theoretical model describing the one-dimensional temperature field within the cavity was developed. The instrumental factor was normalized out by taking the ratio of two signals at the different cavity lengths. Comparison between the theoretical and experimental data for the ratio of signal amplitude (Fig.3) shows good agreement. The analytical model for the thermal-wave cavity response with a liquid intracavity layer permits fitting the theoretical curves to the experimental data to obtain the thermal diffusivity.

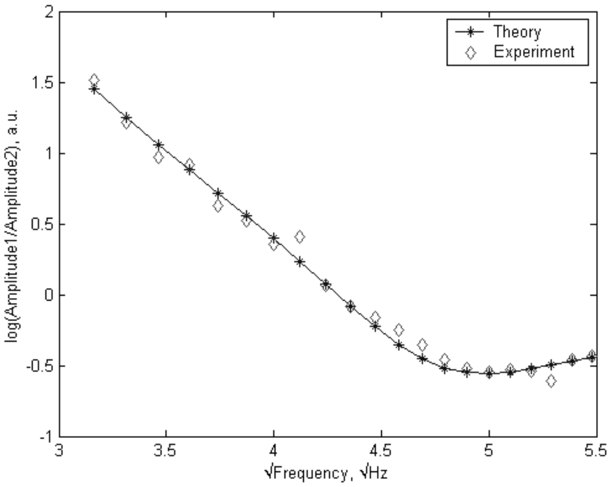

Fig.3. Frequency scan data, water,
$L_1 = 0.42$ mm, $L_2 = 0.65$ mm, $\alpha = 1.462\ 10^{-7}$ m^2/s

The CMRD technique has shown sensitivity of the photothermal signal to methanol in water at the level of 1% by weight. This level is 9% below the lowest reported concentration measurable in this mixture by photothermal techniques.[3] In terms of future applications, environmental pollution concerns require the introduction of simple, robust, inexpensive sensors, which can monitor water quality in remote locations in real time. The proposed system can eventually be implemented into a self-contained in-situ liquid pollution monitor.

References

[1] J.Shen and A. Mandelis, Rev. Sci. Instrum. 66, 4999 (1995).
[2] A. Mandelis, S. Paoloni and L. Nicolaides, Rev. Sci. Instrum. 71, 2440 (2000).
[3] G. Wu, M. Fiebig and A. Leipertz, Int.J.Heat Mass Transfer. 31, 1471 (1988).