

# Chapter Five

## Conclusions and Future Directions

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**T**his work develops two independent high-precision, non-contact, laser-based techniques to precisely measure the index of refraction, concentration, and temperature of liquids. The features of non-contact laser-based techniques include fast response, noninvasiveness, and high sensitivity, which result in their broad use in information storage and retrieval, measurement and inspection, material processing, medicine, and military applications. A HeNe laser serves as a light source, while common alcohols and water-salt solutions are utilized as test liquids. Experimental results are found to be in good agreement with predicted/literature values. The experimental configurations presented in this thesis are small, easy to operate, and inexpensive.

## **5.1 Conclusions of the Present Work**

In Chapter 2, the optical theory governing the present work is presented. First, the fundamental laws in optics—the laws of reflection, and refraction (Snell’s law)—are introduced. Then using the concept of electromagnetic radiation, the propagation of light is described to explain the phenomena of reflection and refraction as a light ray passes through an interface separating two different media. Also the polarization of light and the plane of polarization are defined, with the reflectivity of *p*- or *s*-polarized light and their dependence on incident angle discussed.

Chapter 3 presents a high-precision, non-contact, laser-based technique to measure the refractive index as a function of temperature or concentration, or alternatively, to measure the concentration of a mixture or solution. The essential components in the system include a HeNe laser as the light source, a precision glass cuvette as the liquid container and optical cell, and a high-resolution position-sensing detector and voltmeter. The experimental configuration is compact, reliable and inexpensive. The experiment employs Snell’s law to relate the change of optical path with liquid temperature or concentration, by which the refractive index of liquid can be obtained. In the thermo-optical property measurement, the refractive-index dependence on temperature of two alcohols, ethanol and methanol, is investigated. The refractive-index dependence on concentration of two water-alcohol mixtures is also reported. For the concentration measurement, aqueous solutions of NaCl and MgCl<sub>2</sub> are used as test liquids. This technique can resolve extremely small changes in concentration, on the order of 0.01 %. The results of each measurement are in good agreement with measured values and expected/literature values.

Chapter 4 develops another independent real-time, non-contact, laser-based measurement technique to determine the variations of temperature or concentration at liquid surfaces. A thermorefectance principle using a HeNe probe beam and a pair of PIN photodiodes is adopted to monitor the laser intensity fluctuation from the liquid surface, by which the temperature or concentration at liquid surface can be determined. The experimental configuration does not use a lock-in amplifier, but instead, less expensive, high precision voltmeters. In this work, surface temperature is measured for three pure liquids: 1-propanol, methanol, and ethanol, with very good results found. For a methanol-propanol mixture, the surface concentration is also measured. Both laser-based techniques presented in Chapters 3 and 4, respectively, show potential for a variety of applications requiring real-time, non-contact, remote monitoring of liquid temperature and concentration.

## **5.2 Directions for Future Research**

Some suggestions for future research directions, which emerged during the course of the present study, are outlined below.

### **Laser-Based Refractive Index and Concentration Measurement Technique:**

*Temperature Dependence of Aqueous Solution on Various Concentrations.* The change of index of refraction with temperature ( $dn/dT$ ) is an important, but implicit, parameter for the research in optical measurement and laser-liquid interaction. The limited data for  $dn/dT$  (Lusty and Dunn, 1987; Spear et al., 1990), coupling with the growing interest in non-contact measurement techniques, requires an accurate and

repeatable technique. The laser-based technique discussed in Chapter 3 has the capability of measuring refractive-index dependence on temperature for pure liquids, and the change of index of refraction with temperature for aqueous solution at different concentration will be the future interest of study.

*Diffusion Coefficient in a Binary Mixture.* In a binary mixture, one species may evaporate more rapidly than the other due to different boiling points at a given pressure. As a result, a concentration gradient develops near the free surface. A high-precision non-contact measurement technique without any perturbation is required to determine the concentration gradient in a binary mixture composed of two liquids with different boiling points. Furthermore, the diffusion coefficient in the liquid mixture can be obtained.

*Gravity-Induced Concentration Gradient.* Often the solute of an aqueous solution precipitates, much like pulp settles out of juice. This phenomenon is due to the force of gravity acting upon the difference in molecular weight between the solvent and solute. As a result, the aqueous solution will be no longer uniform. Such gravity-induced concentration gradients are technologically significant in the fields of material processing, critical mixtures, and double-diffusive systems (Bergman et al., 1985; Bergman et al., 1986; Maisano et al., 1976; Greer et al., 1975; Dickinson et al., 1975; Lewis, 1982). The investigation of gravity-induced concentration gradient in an aqueous solution using the real-time, laser-based technique presented in this thesis will be performed.

## **Laser-Based Measurement Technique of Temperature or Concentration at a Liquid Surface**

*Temperature or Concentration Surface Mapping.* After being developed for a single, fixed-point measurement, the real-time, non-contact laser-based technique presented in Chapter 4 will be utilized to measure the temperature or concentration of an entire liquid surface. Measurement of the variations in temperature or concentration of a moving liquid surface is another subject of interest.

*Concentration and/or Temperature-Induced Marangoni Convection.* At a liquid free surface, a temperature change by absorbing a high-intensity short-pulse laser radiation, or an abrupt surface concentration change resulting from adding a second liquid, can alter the liquid surface tension, causing Marangoni convection (Longtin and Hijikata, 1996a, b, c; Longtin et al., 1996; Suzuki et al., 1996; Longtin et al, 1997). Since Marangoni convection only occurs at a liquid surface, temperature measurement of the surface by conventional techniques is ineffective, and a precise non-invasive method without any perturbation is required to monitor and measure the liquid surface phenomena. The laser-based technique presented in Chapter 4 is a candidate for such a measurement.

*Microscale Study on Thermoreflectance.* A microscale study of laser liquid interaction, such as the *p*- or *s*-polarized laser beam being reflected from the air-liquid interface, is also a subject of investigation. It is known that the light will be reflected within a surface layer about  $\lambda/2$  thick (several thousand atoms deep) if the wavelength of the light is much larger than the spacing of the atoms (Hecht, 1987). However, the

microscale research of the correlation about the depth of reflection, dipoles throughout the medium, polarization of light, intensity of laser beam, angle of incidence, and temperature and/or concentration of liquid is not yet thoroughly studied.

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