

Decoupling of thermal effects to image nanometric optical pressure deformation by digital holography

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Abstract: It is evident that thermal effects should not be dismissed when pursuing optical radiation pressure experiments even for transparent media. We have developed a unified model and simulated and tested methods of decoupling the two effects.

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1. Introduction

Measurement of optical radiation pressure effects can be a very useful tool in soft matter physics for the efficient characterization of fluid interfaces and membranes. Although it is one of the most noninvasive methods, very little work has been done in this area due to the difficulty in observing these effects. Surface deformation on a fluid interface by optical radiation pressure using a continuous wave laser source is typically very weak and is often dominated by other effects.

It was our intent to use the method of digital holographic microscopy to image such deformations with nanometric precision and length scales. The quantitative phase analysis inherent to digital holography [1,2], yields an imaging method which can observe very slight surface deformations of standard fluid-fluid interfaces by true continuous wave optical radiation effects. The stable nature of the cw laser is preferred to a pulse laser for improved static surface property determination.

We have found that many studies on optical radiation pressure dismiss thermal effects simply due to the transparent nature of the media under study. In fact, even transparent media can have a thermal effect, particularly, a thermal lens (TL), which is far dominant to the effect of optical radiation pressure. Our use of digital holography as an imaging method has proven to be a valuable indicator of both thermal and optical effects. With our continued work in thermal lensing, it is our goal to decouple these effects so that optical radiation pressure deformations may be easily observed.

2. Theory

A 2D infinite model has been developed to describe the thermal lens effect and the resulting phase shift for a cw laser induced mode-mismatched dual beam set up such as that used in the current study [3]. Maintaining validity of this model through experimental design, the laser induced phase shift within the sample can be described by,

$$\phi = -\frac{P\alpha l (dn/dT)}{\kappa\lambda} \int_0^t \frac{1}{1+2t'/\tau} \left[1 - \exp\left(-\frac{2r^2/w^2}{1+2t'/\tau}\right) \right] \frac{dt'}{\tau} \quad (1)$$

where P is the total excitation beam power at the sample; α is the absorption coefficient; l is the sample thickness; dn/dT is the temperature coefficient of refractive index; κ is the thermal conductivity; λ is the wavelength of the probe beam; r is the radial distance from the excitation beam axis; t is the time of exposure; w is the excitation beam radius (at e^{-2} of its maximum) in the sample; and τ is the thermal time constant (which increases with w^2).

The phase shift associated with optical radiation pressure interface deformation has been derived in [4],

$$\phi = h(n_1 - n_2) \frac{2\pi}{\lambda} \quad (2)$$

where n_1 and n_2 are the refractive index of the first and second media, respectively, and h is a shape function of r .

With these approximations we have developed a computer simulation to combine thermal and optical models to better predict the experimental parameters necessary to decouple the two effects. Figure 1 is an example simulation for benzyl alcohol and water, a promising pair of pure substances that will layer with a previously measured interfacial tension of 3.5mN/m [5].

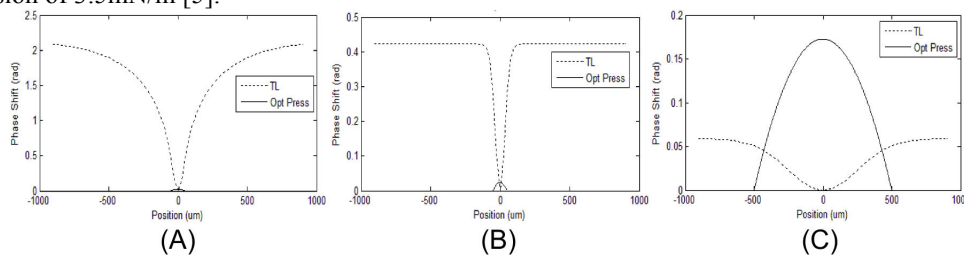


Figure 1. Model prediction for the thermal lens (TL) and optical pressure (Opt Press) effects for a sample of layered benzyl alcohol and water with an interfacial tension of 3.5mN/m . A) 700mW , $50\mu\text{m}$ beam excitation for a 2 second duration. B) Duration reduced to 10ms. C) 5W , $500\mu\text{m}$ beam excitation for 10ms.

3. Methods

Figure 2 shows a diagram of the experimental apparatus. A Mach-Zehnder interferometer is used to create the hologram of the sample using low power ($\sim 2.5\text{mW}$) 633nm laser light delivered by a 50:50 split fiber optic cable (reference/probe beam). An integrated optical excitation arm delivers a high powered 532nm cw laser beam to the sample via a shared microscope objective. A dichroic mirror reflects the excitation beam down onto the sample while allowing the probe beam to transmit up toward the CCD camera placed atop the apparatus. A removable red filter is placed just in front of the CCD camera to filter any green excitation light leaking through the dichroic mirror. This “leaky” light can be used to verify the excitation beam size and location on the sample by temporarily removing the red filter. The hologram is then processed by our LabVIEW personal computer platform for amplitude and phase reconstruction based on the angular spectrum method [6].

A sample is placed in a standard glass cuvette of cross-sectional area, 5mm by 10mm , with a sealable lid. This sample is then placed on the object stage on its side oriented with a 5mm path length. While viewing the phase image, with the optical excitation beam on, the object stage is translated along the beam path (z direction) until the focus of the excitation beam was centered within the sample. At this position, a well defined phase signal, i.e. the thermal lens, is clearly observed (Figure 3). A cross-section through the center of this image is used to plot the profile of the phase shift as a function of radial distance from the z -axis of the excitation beam. The time-resolved model was tested by capturing holograms at high speed to record the entire excitation event in short time intervals.

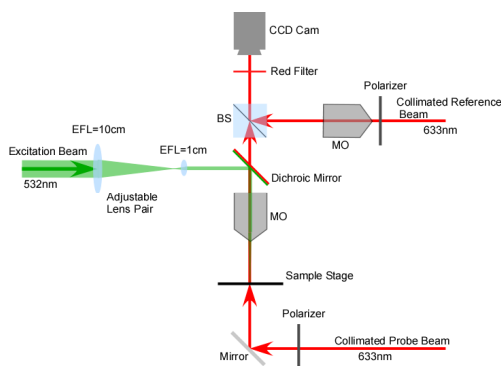


Figure 2: Experimental apparatus (color online). Excitation beam (green); Probe/Reference beams (red); Microscope Objective (MO); Beam Splitter (BS).

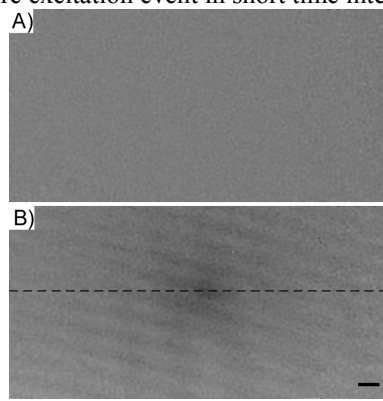


Figure 3: Phase images of a sample, A) with no excitation and B) with optical excitation. Phase scale of images are from 0 (black) to 2π (white) and spatial scale bar is $100\mu\text{m}$. Dashed line indicates the selected cross-section used for further analysis.

4. Results and discussion

We are currently working with benzyl alcohol, which has a measured interfacial tension with water of only 3.5mN/m [5]. Initial simulations suggest that, using our current method, we will be able to successfully observe and

measure the optical pressure induced deformation of this interface on the order of 10's of nanometers. The current setup is under adjustment to allow for the predicted necessary parameters, however, we have performed time-resolved measurements to test the behavior of benzyl alcohol. Figure 4 shows the comparison of these measurements with those predicted by our model with excellent agreement. Once we have characterized our method with such known materials, we aim to determine unknown interfacial tensions by measuring these deformations with high precision.

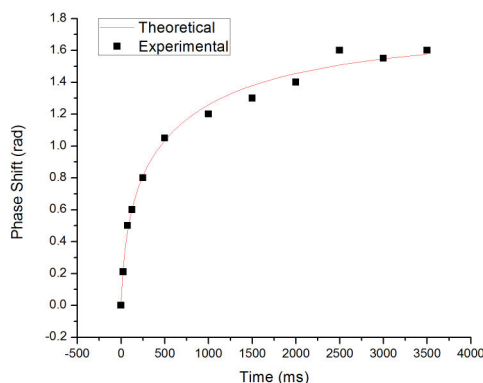


Figure 4. Time-resolved thermal lens phase shift measurements (at $r=900\mu\text{m}$) of benzyl alcohol with model prediction (solid line).

Noise levels of our system were measurement by imaging the sample with no excitation beam present and taking the standard deviation of this phase profile to indicate background noise. Values ranged between .03 and .09 radians during the course of these experiments. The optical path length change, therefore, has been measured to better than 9nm resolution. This is equivalent to a detection level of 15nm to 40nm deformation for the upcoming study of benzyl alcohol and water. It is expected that, with careful isolation and construction, future apparatus could improve this precision by up to an order of magnitude.

5. Conclusion

We continue to make strides in imaging optical and thermal phenomenon with high precision by digital holography. We have implemented a method of reducing our excitation exposure time into the time resolved regime of the 2D infinite model for thermal lensing. The near perfect match between the time-resolved model and our phase measurement is very promising for our near and long term interests. The results of this study and our computer simulations suggest that decoupling the two effects and imaging with digital holography should prove successful for nanometric measurement of optical radiation pressure deformation at fluid-fluid interfaces.

6. Acknowledgements

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7. References

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