

Time-dependent phase response of fluid interface to optical excitation

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Abstract: Optical excitation of a fluid interface involves both momentum exchange and thermal effects. A time-resolved phase study has shown agreement with our combined model of the two effects which vary significantly in time scale.

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1. Introduction

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. In fact, even transparent media can have a thermal effect, particularly a thermal lens, which very quickly becomes far dominant to the effect of optical radiation pressure [1]. The quantitative phase analysis inherent to digital holography [2], offers significant advantages over traditional imaging. Our use of this imaging method has proven to be a valuable indicator of both thermal and optical effects. It has been our goal here to show a detailed time-resolved phase analysis of these effects with good agreement with our model predictions.

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 [3]. This laser induced phase shift within the sample can be described by,

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

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],

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

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 . Note that this effect always results in a positive shift (increased optical path) while a thermal lens typically results in a negative shift.

3. Methods

As shown in Fig. 1, a Mach-Zehnder interferometer is used to create the hologram of the sample using a low power 633nm laser. An integrated optical excitation arm delivers a high powered 532nm cw laser beam to the sample via a shared microscope objective. Holograms are then processed by our LabVIEW software routines to reconstruct both amplitude and phase images using the angular spectrum method [5]. Fig. 2 shows example phase images at points

before and several seconds after the start of excitation. In the currently described study, a sample of water layered on benzyl alcohol (5mm each) is placed on the stage and a 500 μm radius excitation beam of 4W is applied by high speed shutter while capturing holograms at 40fps (25ms/frame).

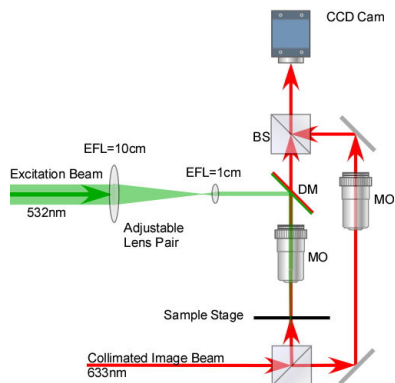


Fig. 1. Experimental apparatus (color online). Excitation beam (green); Imaging beams (red); Microscope Objective (MO); Beam Splitter (BS); Dichroic Mirror (DM).

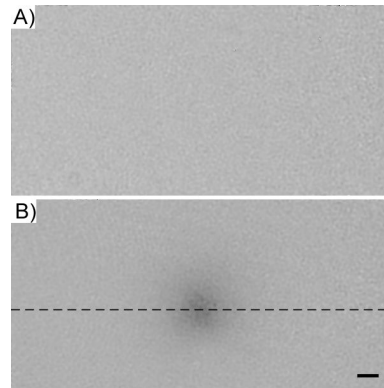


Fig. 2. Phase images of a sample, A) with no excitation and B) with optical excitation (thermal lens). Phase scale of images are from 0 (black) to 2π (white) and spatial scale bar is 100 μm . Dashed line indicates the selected cross-section.

4. Results and discussion

Below, the experimental captures at two time intervals are displayed and compared to our model predictions (Fig. 3). The precise time of the first appearance of the structure is approximated at 5ms (by dataset fit to various model points) followed by the 25ms intervals of the capture rate. The similarities to model predictions demonstrate the soundness and feasibility of the proposed method. Not only is there a clear change of phase shift direction as expected during the transition of effects, but the values of the measured and predicted shifts were in excellent agreement at every 25ms time interval (not all shown). While these preliminary studies are promising, the setup is currently under additional modification for controlled image capture at the time scales proposed. The excitation beam will trigger a controlled microsecond resolved delay response from the camera to capture precise moments in time of the event.

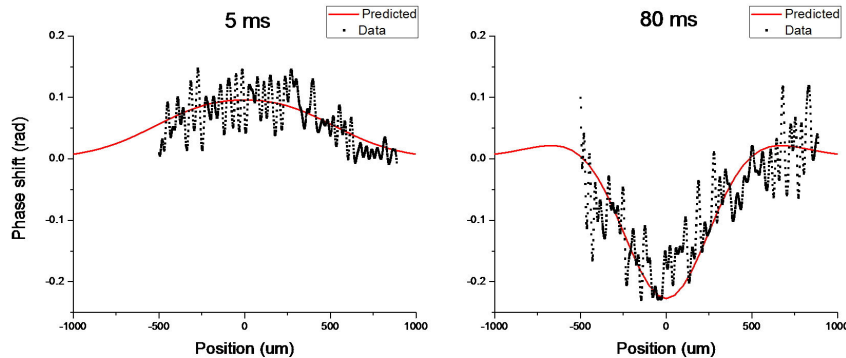


Fig. 3. Data (scatter) and model predictions (solid) at two example points in time during an excitation event.

5. References

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