Radiation Force Effect at the Dielectric Water-Air Interface

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Abstract

Introduction:
The effects of radiation pressure exerted on a dielectric surface exposed to electromagnetic radiation has been a long-standing debate for over a century. The effect can be interpreted as the transfer of momentum from photons at the surface in the direction of propagation of the incident electromagnetic radiation [1].

Apparent conflicting theories for the energy-momentum tensor have been proposed by Minkowski in 1908 and Abraham in 1909 to explain this effect. Minkowski theory predicts that the transfer of momentum produces an outward surface force (surface expansion) in the medium, the momentum would be proportional to its refractive index n as pM = np0, in which p0=U/c is the photon momentum in the vacuum, U is the energy of light, and c is the speed of light. In contrast, Abraham representation leads to a momentum within the medium in the form pA = p0/n, which, in turn, produces an inward force to the medium (surface contraction).

At the theoretical level, the Minkowski-Abraham controversy has apparently been resolved by identifying the Abraham momentum as the kinetic momentum and the Minkowski momentum as the canonical momentum [2]. Yet there has been so far only limited experimental tests and simulations of our understanding of radiative transfer between electromagnetic radiation and dielectric media.

Use of COMSOL Multiphysics® software:
The radiation force effects on the surface displacement can be calculated by solving the Navier-Stokes equation with appropriated boundary conditions. The surface deformation can be described by the radiation pressure as well as those forces due to gravity and surface tension. We applied the finite element analysis (FEA) method for the numerical calculations using the COMSOL Multiphysics® software, "Laminar Two-Phase Flow, Moving Mesh" physics interface. This method is used to model two fluids separated by a fluid interface and where the moving interface is tracked in detail. The model was built in the 2D axisymmetric geometry. There are three types of boundaries in the model domain, one boundary representing the axis of symmetry, two boundaries are modeled with no slip conditions, and one free surface on which the external pressure and surface tension acts.

Results:
Figures 1 and 2 display the actual deformation of water at different exposure times. Under continuous excitation, the liquid surface rises with time reaching a maximum deformation of around 30nm at the center of the excitation beam, Figure 1. As for the pulsed excitation, a sharp peak appears at short time, which is dispersed rapidly on the surface, Figure 2.

We used the photomechanical mirror (PM) method to measure the time-evolution of the nanometer deformation generated on the water surface due to the radiation forces by exciting the sample either with continuous or pulsed laser beams. Figure 3 shows the experimental data (circles) and the calculated PM signals (continuous lines).

Conclusions:
The numerical predictions are in excellent agreement for both the continuous and pulsed excitation transients. In fact, it shows quantitatively that the effects of radiation forces in water can be fully described.

Reference

1. N. Astrath et al., Unraveling the effects of radiation forces in water, Nature Communications, 5, 5363 (2014).

2. R. Pfeifer et al., Colloquium: Momentum of an electromagnetic wave in dielectric media. Rev. Mod. Phys., 79, 1197-1216 (2007).

Figures used in the abstract

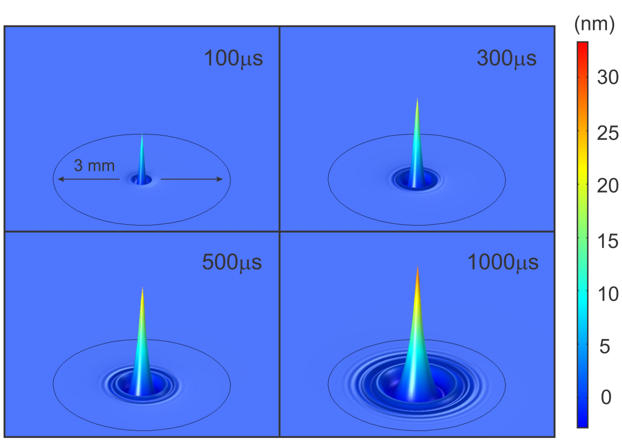

Figure 1: Water surface deformation under continuous excitation.

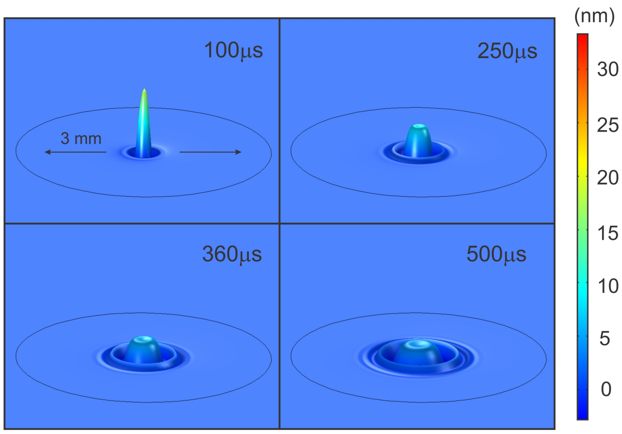

Figure 2: Water surface deformation under pulsed excitation.

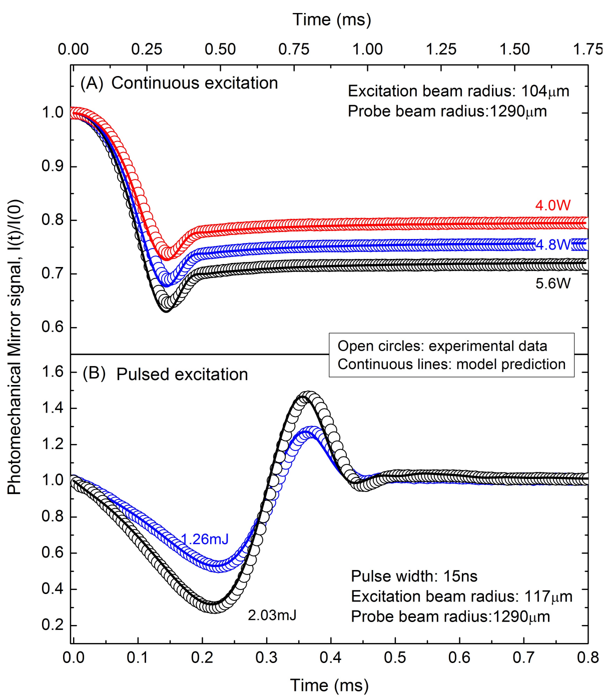

Figure 3: Photomechanical mirror signals.