Analysis of a Plasma-Mediated Photoacoustic Response From Plasmonic Nanoparticles in Ultrashort Regime

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Abstract

Over the last decade, plasmonic nanoparticles (PNPs) have received growing interest as exogenous contrast agents in the thermal expansion based photoacoustic (PA) imaging technique in biomedical applications [1]. Such functionality is due to the localized surface plasmon resonance (LSPR) created by the light-induced coherent oscillation of the conduction electrons in the PNPs. In the near-field the LSPR is also able to enhance the incident electromagnetic field and result in amplified electric field near the NP surface.

In the conventional PA imaging technique the energy is deposited within PNPs by a short-pulsed laser, leading to thermal expansion of PNP and surrounding materials out of which the PA signal is generated. In order to achieve desirable results, the PNPs are irradiated at the LSPR wavelength peak; however, this on-resonance irradiation might lead to PNP melting or fragmentation.

In this study, instead of short-pulsed lasers, we use ultrashort-pulsed lasers (100 femtosecond - 2 picosecond) to interact with PNPs in PA imaging technique. The reason is that the ultrashort-pulsed lasers can provide high peak intensity with low pulse fluence. In addition, depending on the peak intensity, the ultrashort pulsed laser's interaction with matter can lead to highly localized free electron density (plasma) formation through nonlinear effects such as multiphoton and impact electron excitation [2]. Enhanced by the PNPs, the ultrashort-pulsed laser can cause plasma nucleation around the particles at even lower pulse fluences. Also in this process it is possible that a considerable number of electrons be ejected from the surface of PNPs due to thermionic emission in the materials and participate in the plasma generation. Once nucleated, the plasma can absorb more energy during the pulse and the energy deposition in plasma can be more than that within the PNP itself [3, 4]. The plasma nucleation can happen even if the PNPs are irradiated by an off-resonance wavelength where the filed enhancement is enough to generate plasma. As a result, the energy absorption on the nucleated plasma within the PNPs' surrounding material can be used as a source of energy for thermal expansion in PA imaging.

In this presentation, we show how the finite element analysis with COMSOL Multiphysics® software is used to simulate the significant impact of energy deposition in plasma surrounding the

PNPs on PA wave propagation when PNPs are irradiated by ultrashort pulses [4]. To do this, the COMSOL software model is built based on the following physical phenomena that are one-way coupled: 1) optical properties of the PNP obtained from simulation of electromagnetic wave interaction with PNP and coupled through resistive heating due to laser pulse to; 2) two temperature model to analyze transient heat transfer in ultrafast regime and temperature increase calculation, where temperature is used as a coupling parameter to; 3) plasma dynamics and 4) structural mechanics analysis for linear thermal expansion, stress and strain calculation for the input as a boundary condition in acoustic-structure interaction for; 5) acoustic pressure wave propagation modeling.

Reference

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Figures used in the abstract

Figure 1

Figure 2

Figure 3

Figure 4