Numerical Analysis of Laser Induced Photothermal Effects using Colloidal Plasmonic Nanostructures

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Introduction

Laser induced photothermal heating of plasmonic nanoparticles that have been uptaken by malignant cells has proven to be an effective minimally-invasive cancer treatment. The therapy is based on efficient heating of the particles when irradiated at their **Localized Surface Plasmon Resonance (LSPR)**[1,2]. At **LSPR** there is a collective and coherent oscillation of free electrons that results in intense absorption and scattering of incident light, as well as highly localized field enhancement. The particles are heated with sufficient intensity to produce nanobubbles that damage the cell membrane resulting in lysis.

Gold Nanocages have recently been investigated for use in photothermal therapy. These are hollow nanostructures with porous walls that have several attractive features:

- ❑ Their size can be tuned during synthesis and kept small enough to increase blood half-life.
- ❑ The LSPR wavelength can be tuned to the "biological window" in the NIR (700 - 1100nm)
- ❑ They can be treated with various functional groups to enable functionalization with therapeutic and imaging agents[3-5]
- ❑ Our research indicates that colloidal nanocages maintain high absorption over a wide range of orientations relative to the polarization of the incident field

Objectives: Perform computational modeling to advance understanding of using gold nanogages to generate plasmonic nanobubbles (PNBs)

- ❑ PNBs can be generated on-demand with high temporal and spatial resolution
- ❑ PNBs can be used to inflict direct mechanical damage to a cell's membrane thus nullifying the requirement for specialized drugs[6,7]

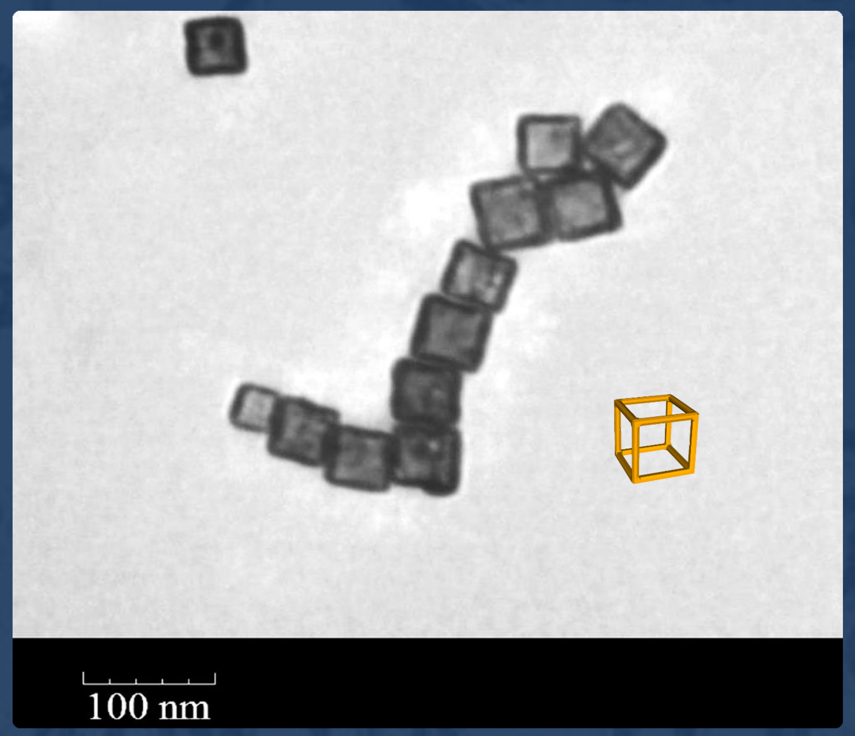

Figure 1. Transmission electro micrograph (TEM) of gold nanocages with inset of modelled geometry. Pictured nanoparticles have been coated with polyvinyl pyrrolidone (PVP)[8]

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Theory and Modeling

Computational Photonic and Thermo-Fluidic Analysis

Photonic Analysis

The photonic analysis is performed using computational electromagnetics and is used to predict the time-averaged power absorbed by plasmonic nanoparticles as a function of the wavelength, intensity and polarization of the incident light. Maximum power absorption occurs at the plasmon resonance wavelength.

We use TEM analysis where the equation for the E-field reduces to:

$$\nabla \times (\mu_r^{-1}\nabla \times E) - k_0^2\left(\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}\right)E = 0$$

where μ_r and ε_r are the relative permeability and permittivity of the media, respectively.

Thermo-Fluidic Analysis

The fluidic analysis is performed using CFD and is used to predict thermal, pressure and flow effects including the temperature rise in the particle, heat transfer from the particle to the fluid, phase change within the fluid leading to homogeneous bubble nucleation, the dynamic behavior of the bubble as it expands and collapses, and the temperature, pressure and flow throughout the fluid during the entire process. The fluidic analysis is used to determine the threshold power and pulse duration needed to generate and sustain a bubble with a desired dynamic behavior. Once this is understood, the laser intensity needed to produce the threshold power within the particle is back-calculated from the photonic analysis.

The equations governing heat and mass transfer are as follows:

Navier-Stokes

$$\rho\left(\frac{\partial v}{\partial t} + v\cdot\nabla v\right) = -\nabla p + \mu\nabla^2 v$$

Continuity

$$\nabla \cdot v = 0$$

Heat Transfer

$$\rho\, c_p\left(\frac{\partial T}{\partial t} + v\cdot\nabla T\right) = k\nabla^2 T, \qquad \textit{(fluid)}$$

$$\rho_{np}\, c_{np}\frac{\partial T_{np}}{\partial t} = Q_{abs}(t) + k_{np}\nabla^2 T_{np}, \qquad \textit{(nanoparticle)}$$

Photonic Analysis

We use computational electromagnetics to quantify the energy absorption of colloidal nanorods and nanocages to determine the heating efficiency as a function of **orientation** relative to the incident polarization.

➢ The **orientation** can be specified using angles θ and φ that define the rotation of axis of the particle relative to the x- and z-axis (see **Figure 3**).

Nanorod Analysis

- The length and diameter of the nanorod are 60 nm and 17 nm.
- There are two distinct LSPR frequencies that correspond to transverse and longitudinal polarization modes.
- A higher LSPR frequency occurs for transverse alignment (θ=0˚, φ=0˚), whereas a lower resonant frequency is obtained for parallel alignment (θ=90˚, φ=0˚) relative to the source.

Nanocage Analysis

- This geometry is defined by its edge length and thickness, a and t, respectively. We compute the absorption spectra for a nanocage with a = 50 nm and t = 5 nm, i.e. a 50 nm hollow cube structure with a 5 nm thick frame.
- The resonance peak for the nanocage remains almost constant independent of orientation

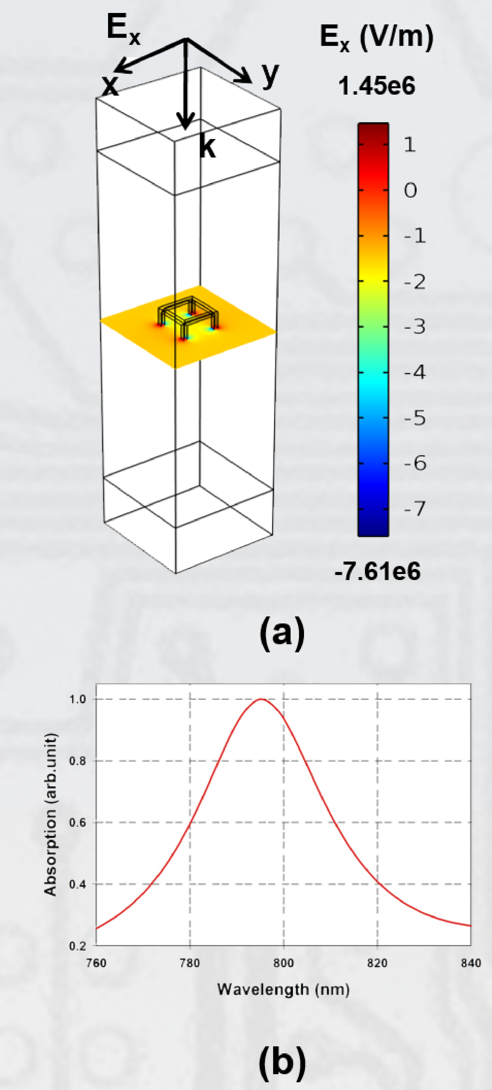


Figure 2. Photonic analysis of a gold nanocage (a= 50 nm and t = 5 nm) with parallel alignment to the incident polarization: (a) Computational domain and plot of Ex through a cross section of the domain, (b) absorbed power vs. wavelength at parallel orientation

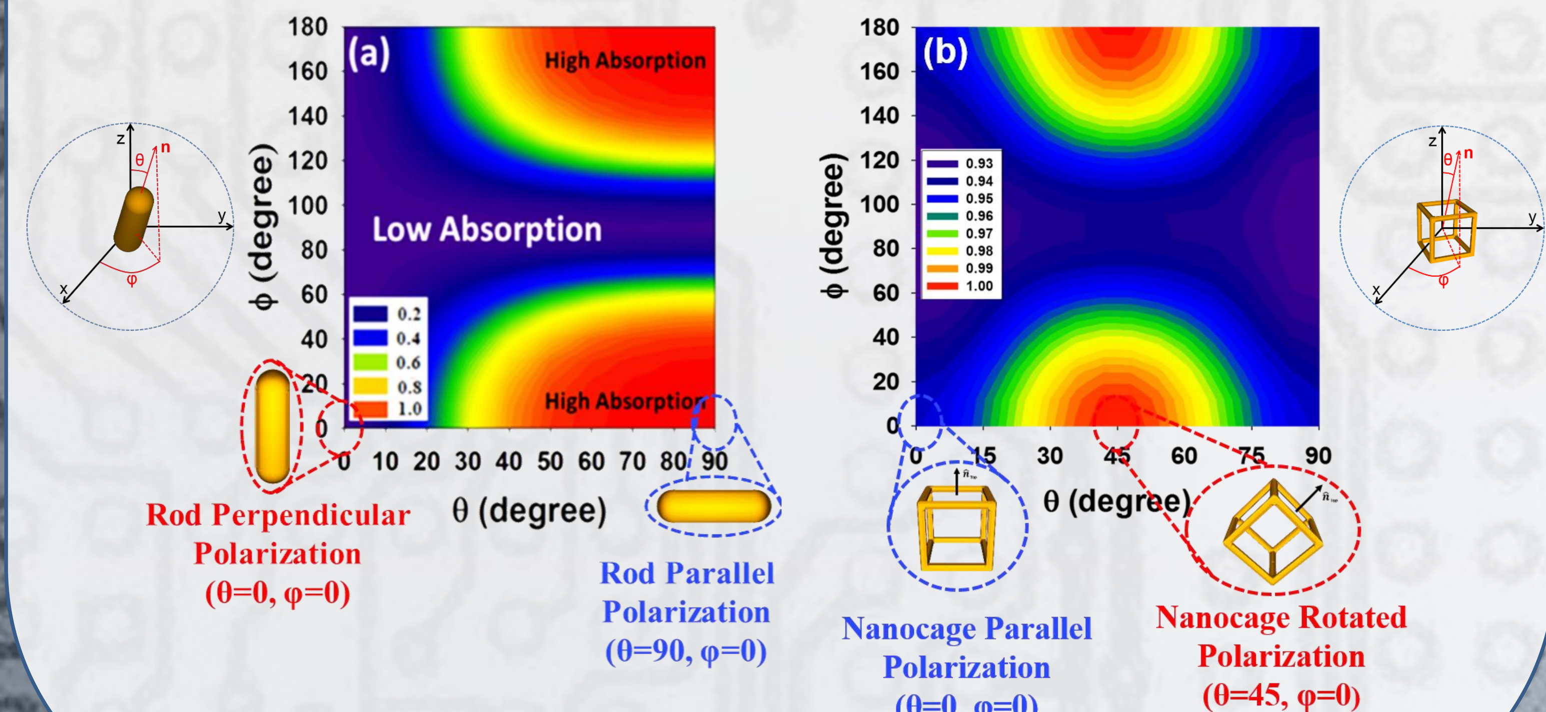


Figure 3. Normalized peak absorption at respective fixed LSPR wavelengths as a function of particle orientation (θ, φ): (a) nanorod at λ = 770 nm ,(b) nanocage at λ = 795 nm .

Thermo-Fluidic Simulations

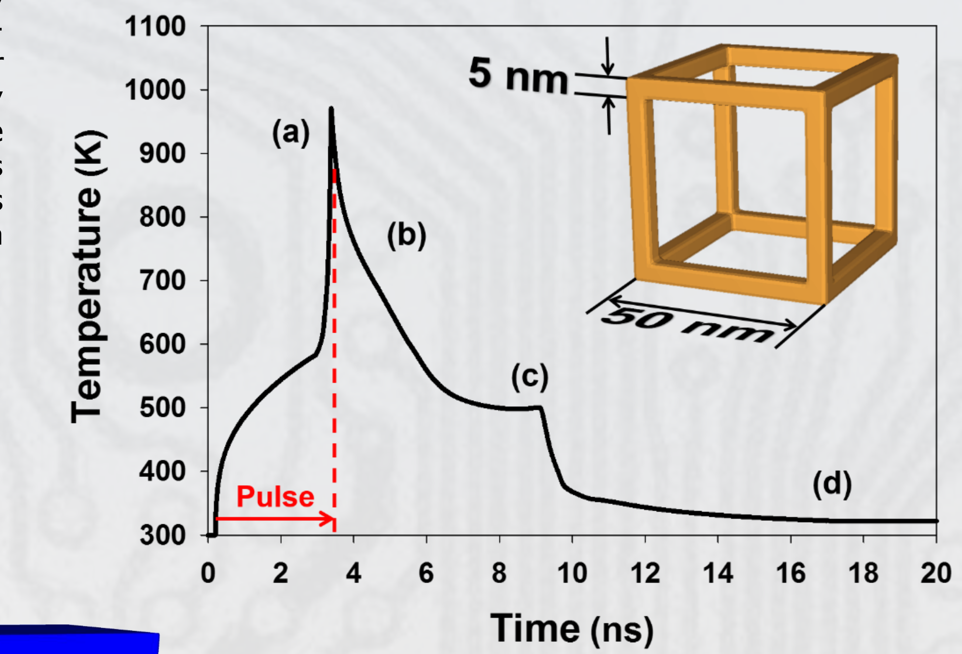
CFD simulations were performed to study the pulsed photothermal cycle of various gold nanoparticle geometries as defined in Table 1.

Nanoparticle Type	Dimensions (nm)	Power (μW)	Pulse Duration (ns)	Laser Irradiance (mW/μm²) (λ nm)	Maximum Nanoparticle Temperature (K)	Maximum Bubble Radius (nm)	Nucleation Time (ns)	Nanobubble Lifetime (ns)
Nanosphere	R=30	152	5	14 (532)	1080	50	3.8	5.6
Nanorod	L=60, r=8.5	76.8	1.9	10 (770)	915	65	2.7	3
Nanoring (h=20nm)	R=50, r=30	252	4	27.07 (935)	862	95	3.5	6.3
Nanotorus	R=40, r=10	259.2	3.1	21.82 (986)	889	70	2.7	4.9
	R=30, r=10	172.8	4.1	10.06 (825)	1000	80	3.4	5.4
Nanocage	a=50, t=5	180	3.18	12.98 (795)	977	120	2.8	6.8

Table 1. Summary of nanoparticle geometries with heating and nanobubble parameters.

Thermo-Fluidic Analysis

Compared to previously studied geometries[1,2] nanocages do not exhibit some kind of axial symmetry. Therefore, a more complicated full 3D CFD analysis was performed so as to determine the pulse duration and power required for the nucleation of a nanobubble without damaging or melting the nanocage. A Cartesian 3-D model of one octant of the nanocage, due to symmetry, was used with a computational domain that spanned 180 nm in the x, y and z directions. A non-uniform mesh of 1nm cells for the first 100 nm and gradually resized to 2 nm cells for the next 80nm in all dimensions was used. Simulation runtime is approximately 252h on a standard hex-core workstation



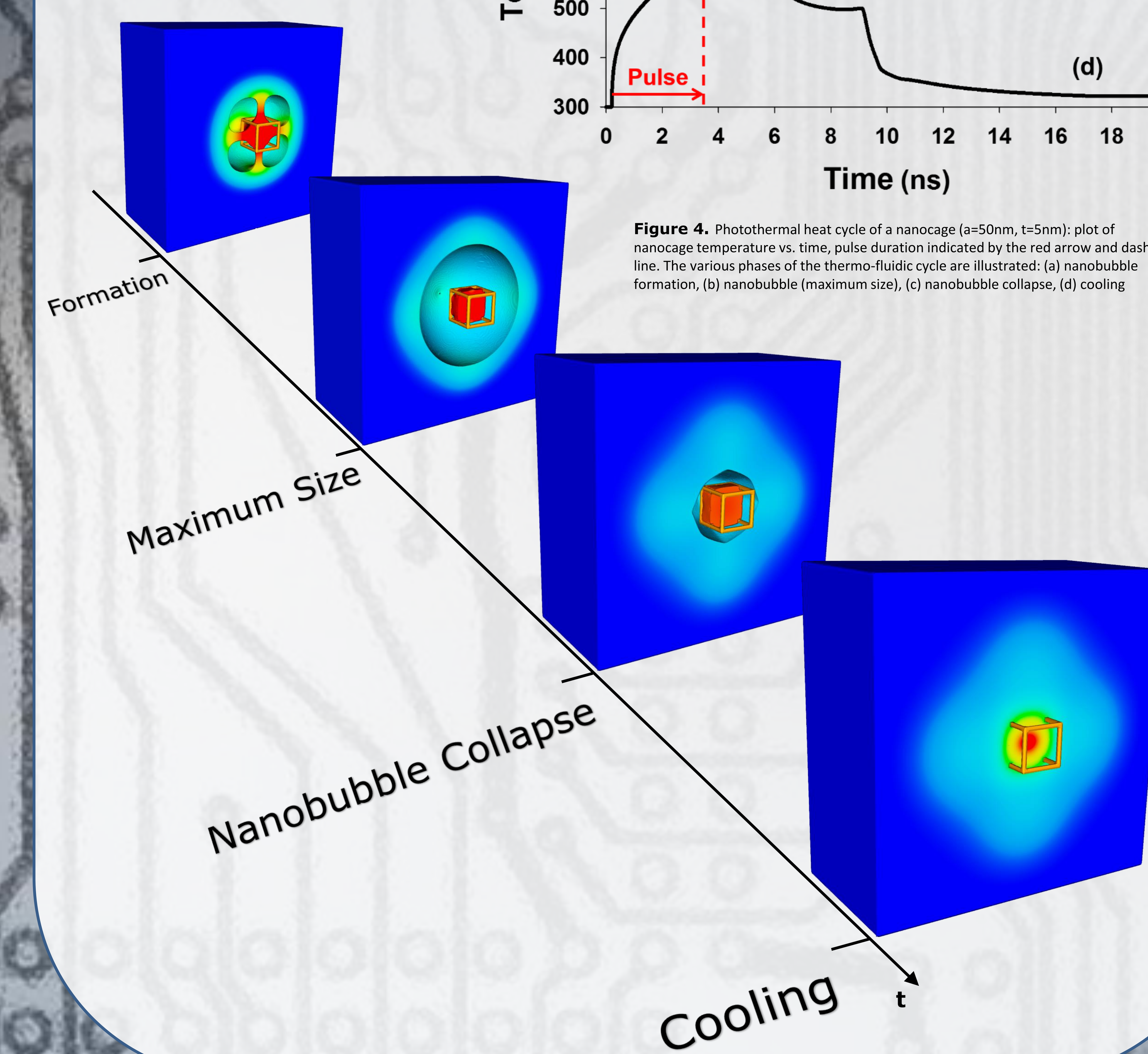


Figure 4. Photothermal heat cycle of a nanocage (a=50nm, t=5nm): plot of nanocage temperature vs. time, pulse duration indicated by the red arrow and dashed line. The various phases of the thermo-fluidic cycle are illustrated: (a) nanobubble formation, (b) nanobubble (maximum size), (c) nanobubble collapse, (d) cooling

Conclusions

A photonic analysis to determine the absorption spectra of nanorods and nanocages as a function of their orientation with respect to the incident polarization and a thermo-fluidic analysis to determine the absorbed power and pulse duration needed to heat the nanoparticles to create sustained nanobubbles were performed.

- A combination of photonic and thermo-fluidic analysis provides insight into fundamental aspects of the photothermal process and **enables rational design for novel applications**.
- Colloidal plasmonic nanocages have **advantageous absorption properties** for photothermal applications (as compared to core shell and nanorod particles) because their resonant absorption can be easily tuned to NIR wavelengths during synthesis and their level of **absorption remains relatively high over a broad range of orientations**.
- These properties hold potential for applications such as photothermal cancer therapy as they can enable more **efficient heating of malignant tissue** and **access to deeper tumors**.