Investigating Tagging Efficiency in Ultrasound-Modulated Optical Tomography

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Motivation

- Ultrasound-modulated Optical Tomography (UOT) allows for optical imaging deep inside biological tissues with ultrasonic resolution.
- In UOT, a fraction of the photons passing through the ultrasound beam are modulated, or "tagged". Detection of the tagged photons gives rise to improved resolution.
- The modulation efficiency is well characterized in transparent media, but is still relatively unstudied for the case of scattering media. oo

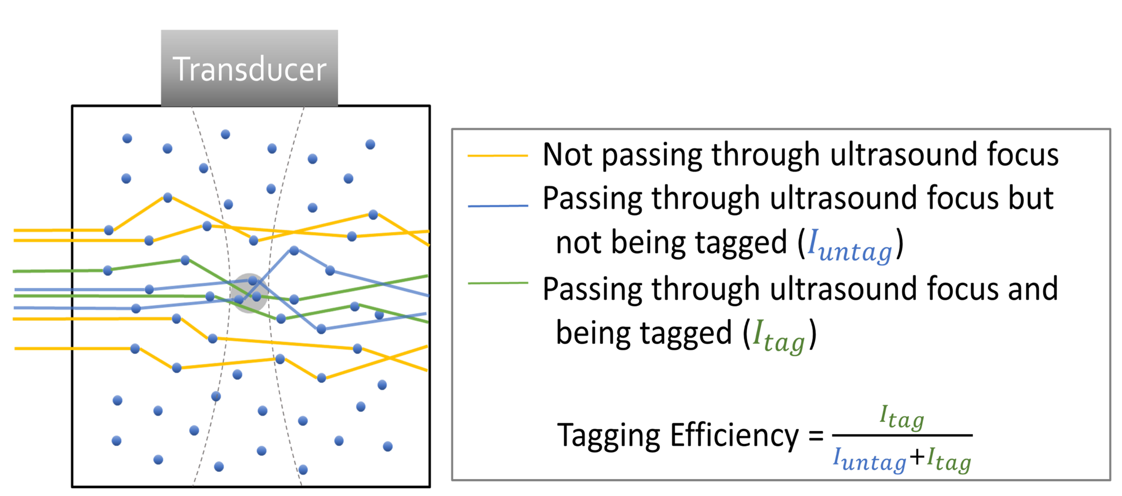
Goal: to investigate the tagging efficiency and mechanism in scattering media

Ultrasound-Modulated Optical Tomography (UOT)

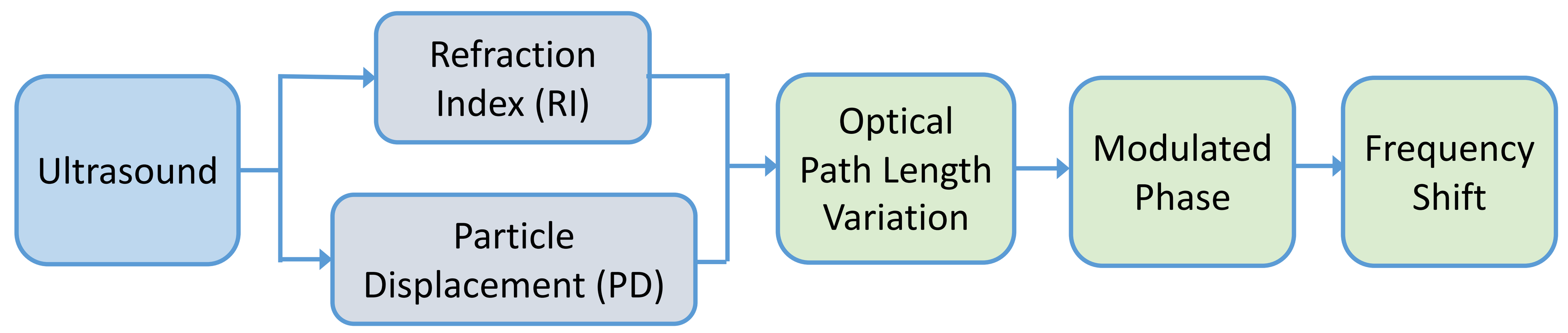
- UOT uses a focused ultrasound beam to set the imaging resolution.
- The tagged light is frequency shifted to $\omega \pm m\omega_{us}, m = 1,2,3 \ldots$, where ω is the frequency of the unmodulated light, and ω_{us} is the frequency of the ultrasound.
- The modulated light can be detected using interferometry, with the reference beam shifted to $\omega + a\omega_{us}$, where a is set to the specific order of interest.
- The intensity on the detector can be expressed as

$$< |E_{untag}\, e^{i(\omega t+\phi_u)} + E_{tag,m} e^{i((\omega \pm m\omega_{us})t+\phi_m)} + E_{ref} e^{i(\omega + a\omega_{us})t}|^2 >$$
$$= |E_{untag}|^2 + |E_{tag}|^2 + |E_{ref}|^2 + 2E_{tag,a}E_{ref}\cos\phi_a$$

- Tagging Efficiency $\eta = \frac{I_{tag}}{I_{total}}$ describes the fraction of light passing through the ultrasound that is tagged.
- Tagging efficiency impacts the signal-to-noise ratio in UOT.

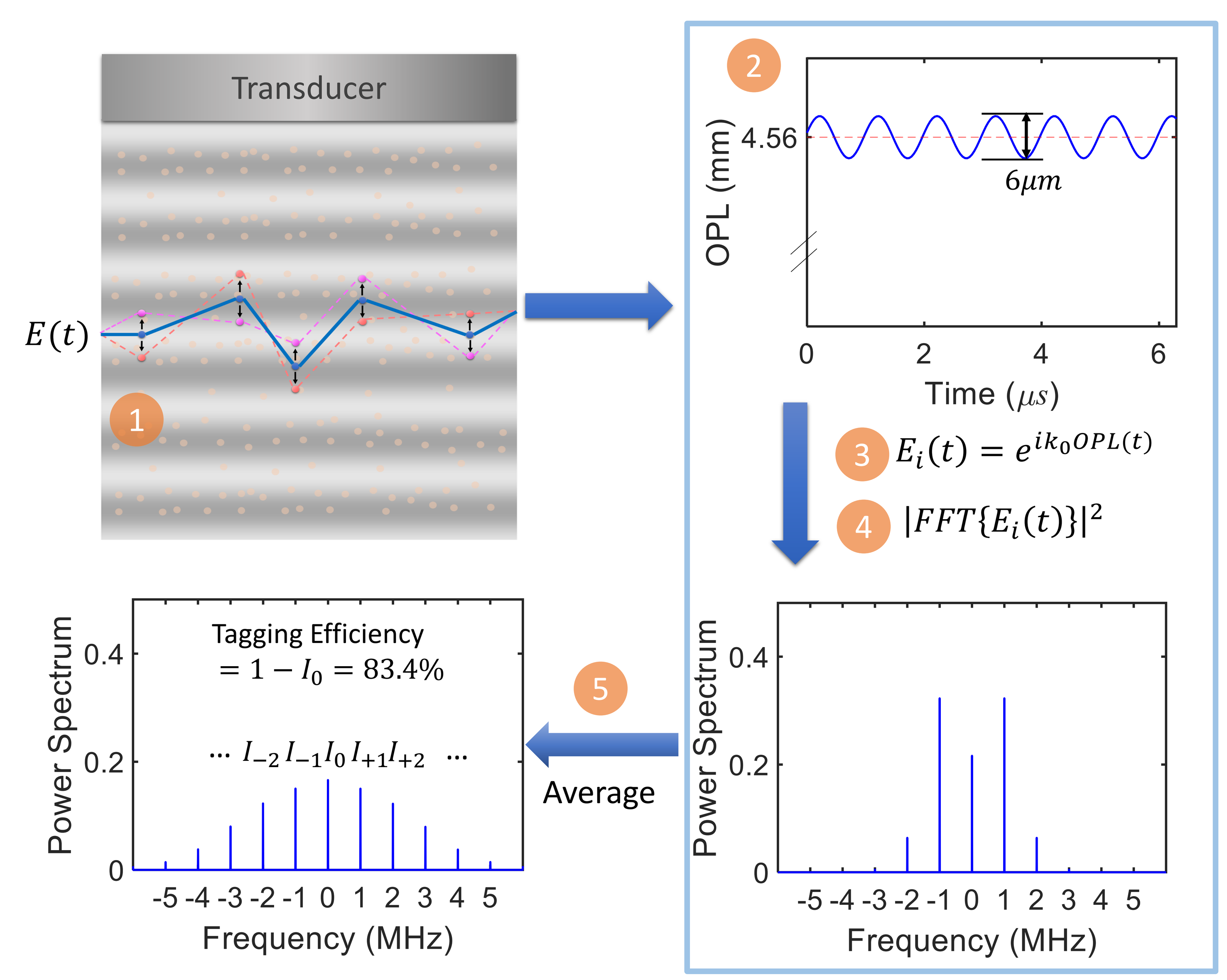


Modulation Mechanisms



- Ultrasound tags light using two methods[1]:
  - Refraction Index (RI) Modulation
    - Ultrasound causes refractive index variation in the media.
    - This mechanism is also known as Raman-Nath diffraction in transparent medium.
  - Particle Displacement-Induced (PD) Modulation
    - Ultrasound causes small displacement in the particles, which modulates the trajectories of the scattered light .
- The photon that passes through the ultrasound beam experiences a modulation in optical path length due to these two mechanisms.
- Modulated phase gives rise to the frequency shift.

Simulation Method



1. Using Monte Carlo, generate trajectories of photons travelling in the medium[2].

For each detected photon:

2. Calculate the modulation in optical path length due to RI and PD.
3. Calculate the E-field for each photon packet as $E(t) = e^{ik_0 OPL(t)}$.
4. Calculate Power spectrum of each photon packet as $|FFT\{E(t)\}|^2$.

5. Average the calculated power spectrum from each of the photon packets. From the average power spectrum, the tagging efficiency is: $\frac{1-I_0}{I_{total}}$.

Parameters:

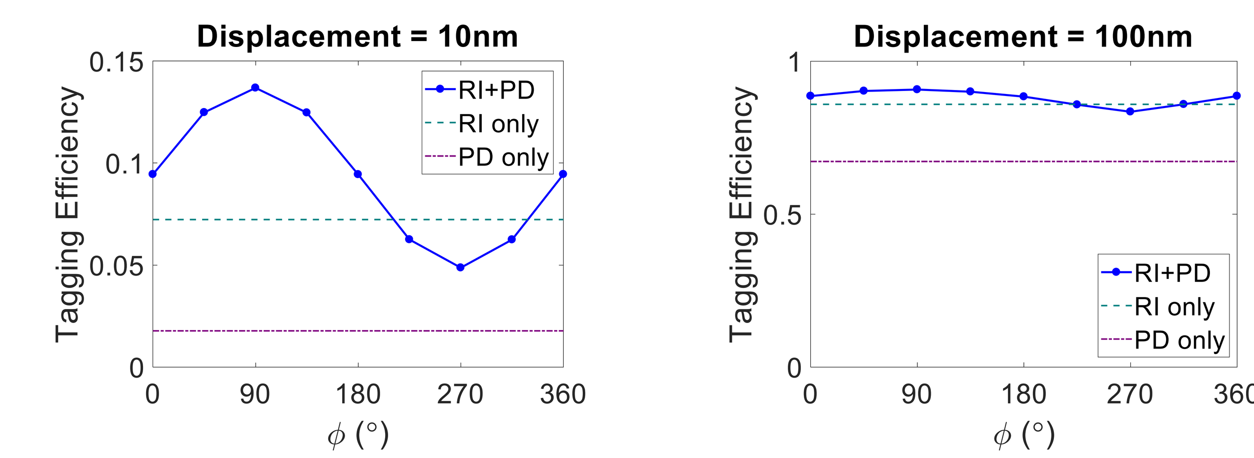
- μ_s : 10 mm^{-1} if not specified
- g : 0.9
- Ultrasound Frequency = 1 MHz
- Ultrasound Velocity = 1480 m/s

- Background medium
  Refraction Index: 1.33
  Density: 1000 kg/m^3

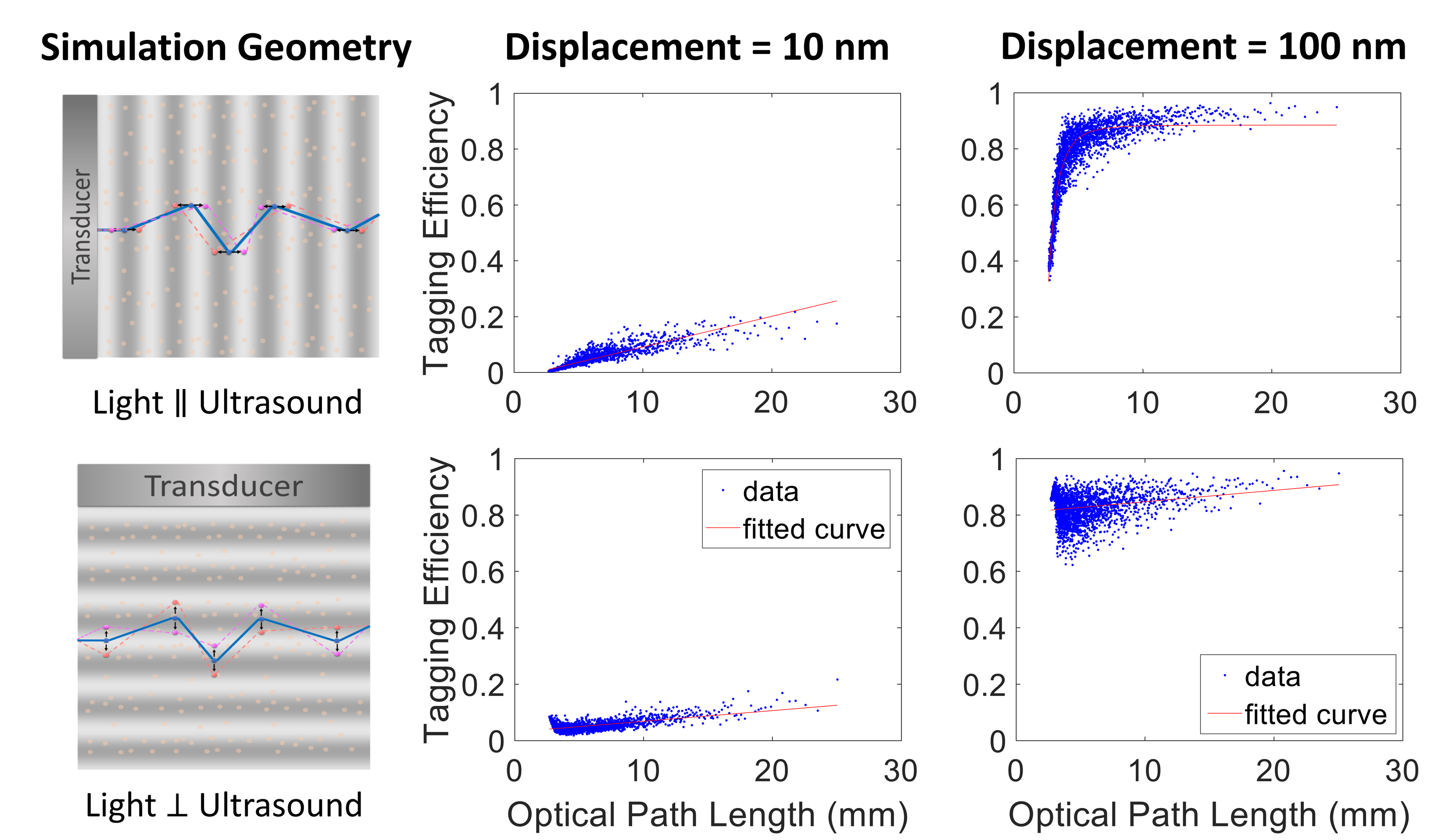
Combined Effect of Two Modulation Mechanisms

- Let the ultrasonic pressure have the form $P(x,t) = P_0 \sin(\omega t - kx)$.
  - Particle displacement: $D(x,t) = \frac{P_o}{\rho\omega v}\sin(\omega t - kx + \phi)$
  - RI modulation: $\Delta n = n_0 \left(\frac{\partial n}{\partial p}\right) P(x,t)$

  where $\frac{\partial n}{\partial p}$ is the adiabatic piezo-optical coefficient of background medium.
- In biological tissue, the particle displacement is similar in phase and amplitude to the movement of the background medium[3].
- In this regime, ϕ = 270° , and the two mechanisms counteract each other.



Tagging efficiency versus Optical Path Length (OPL)



- To acquire photons with different OPLs, μ_s was swept from 4 mm^{-1} to 20 mm^{-1}.
- The thickness of the medium was 2mm (along the direction of light propagation).
- Tagging efficiency increased with increased scattering (longer OPL).
- When OPL is short (scattering is weak), light propagates normal to ultrasound has higher tagging efficiency than light propagates parallel to ultrasound.
- The ultrasound-induced modulation results in an modulated OPL that oscillates at ultrasound frequency.
- Tagging efficiency is positively correlated to the amplitude of the oscillations.

Discussion and Future Work

- Tagging efficiency can be above 80%, for example when particle displacement is 100 nm.
- Tagging efficiency can be higher in scattering media than in transparent media.
- We plan to experimentally verify the results by looking at tagging efficiency in phantom with different μ_s.

References

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2. Fang, Qianqian, and David A. Boas. "Monte Carlo simulation of photon migration in 3D turbid media accelerated by graphics processing units." *Optics express* 17.22 (2009): 20178-20190.
3. Sakadžić, Sava, and Lihong V. Wang. "Correlation transfer and diffusion of ultrasound-modulated multiply scattered light." *Physical review letters* 96.16 (2006): 163902.

Acknowledgements

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