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Acousto-optic Imaging in the Near Infrared: Optimization and Quantitative Characterization of the System



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Abstract: Acousto-optic (AO) imaging is a new dual-wave modality that combines ultrasound with diffuse light to achieve deep-tissue imaging of optical properties with the spatial resolution of ultrasound. In this technique, the sample is simultaneously insonified by an ultrasound beam and illuminated with a laser source. The ultrasound modulates the optical field in the interaction region, and detection of the modulated optical field gives an indication of the strength of the AO interaction. We have previously demonstrated that a photorefractive crystal (PRC) based optical detection system can be used to detect the AO response generated by pulsed ultrasound from a commercial medical scanner (Analogic AN2300) *in vivo*. In order to overcome the limitations of imaging depth and relatively long response time of the former AO imaging system working at an optical wavelength of 532 nm, a new setup operating in the near-infrared (NIR) wavelength range using a GaAs photorefractive crystal has been developed. We demonstrate that the response time of the GaAs PRC can be on the order of 1-10 ms, which is sufficient to overcome speckle decorrelation and is thus suitable for *in vivo* measurements. Progress towards optimization of the NIR AO imaging system is detailed. In addition, preliminary experimental results demonstrating the detection of an optical absorber in both low and highly scattering tissue phantoms are presented.

Motivation

- ULTRASOUND IMAGING**
 - Image Contrast: Acoustic properties (density, speed of sound)
 - Advantage: High resolution
 - Problems: Less reliable in diagnosing cancers
- OPTICAL IMAGING**
 - Image Contrast: Optical properties (absorption, scattering)
 - Advantage: Functional Imaging -Molecular Structure
 - Problems: trade-off between imaging depth and resolution
- IMPROVEMENT-ACOUSTO-OPTIC IMAGING (AOI)**
 - AOI: A dual-wave sensing technique using ultrasound-modulated optical diffuse light
 - Advantage: optically relevant physiological information + ultrasonic spatial resolution
 - Fusion of AOI and diagnostic ultrasound: Simultaneously obtain and register both acoustic and optic information

State of the Art

- Marks *et al.*¹ first reported the modulation of diffuse laser light with pulsed ultrasound in 1993;
- Wang *et al.*² used CW light and CW focused ultrasound to image inhomogeneities in diffuse media;
- Boccaro *et al.*³ designed a parallel detection scheme to improve the SNR in the detection of the speckle modulation of coherent laser light modulated by CW focused ultrasound;
- DiMarzio *et al.*⁴ combined DOT with focused ultrasound with the aim to create virtual diffusive wave sources;
- Boccaro *et al.*⁵ introduced the idea of combining AOI and ultrasound images using CW based AOI;
- We⁶ developed a photorefractive-crystal (PRC) based interferometry system at an optical wavelength of 532 nm to enhance detecting AOI signals using pulsed ultrasound, improving the axial resolution;
- We⁶ achieved a direct fusion of AOI and B-mode images with a commercial pulsed ultrasound scanner;
- We recently developed the system into near-infrared wavelength, potentially suitable for *in vivo* measurements.

Theoretical Consideration

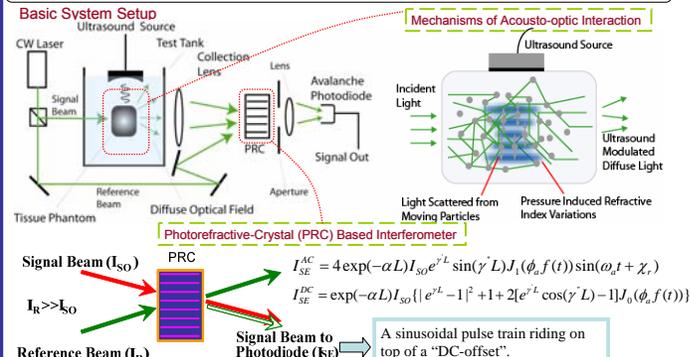
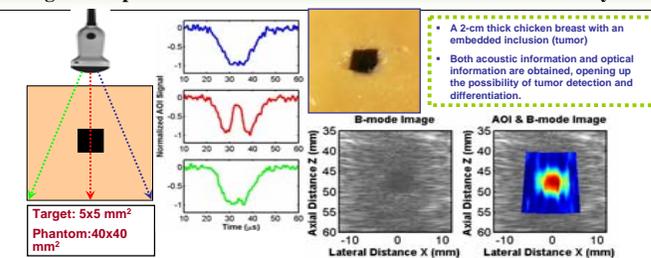
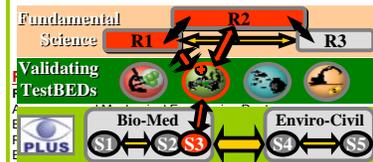


Image Principle and Previous Results Obtained at 532 nm/BSO Crystal



3-Level Diagram

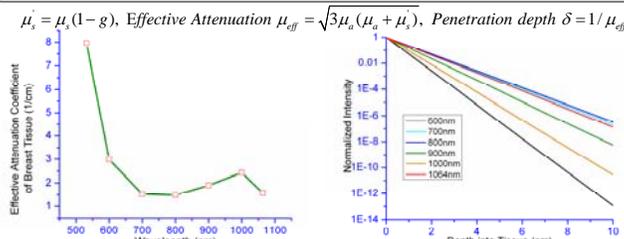


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Light Propagation in Breast Tissue

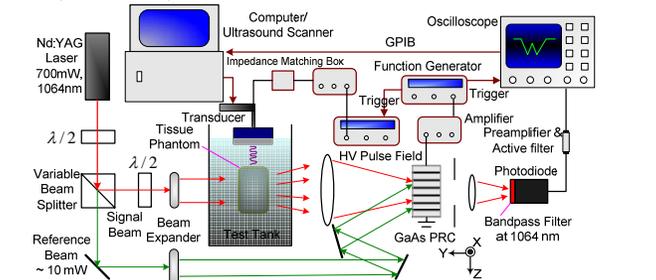


Wavelength (nm)	532	600	700	800	900	1000	1064
Effective Attenuation Coefficient (cm ⁻¹)	7.97	2.98	1.53	1.49	1.90	2.43	1.58
Penetration Depth (cm)	0.13	0.34	0.65	0.67	0.53	0.41	0.63

AO Imaging in the Near Infrared

- Technological Challenges in the Transition to In-Vivo Application**
- Relatively high scattering coefficient and effective attenuation coefficient at the optical wavelength of 532nm limit the imaging depth;
 - The response time of BSO PRC (around 150 ms) insufficient to respond to physiological motion, which results in the formation of time varying speckles → on the order of milliseconds.
- Solution: Develop AOI System Operating in the Near-Infrared (NIR) at 1064nm**
- Lower scattering/effective attenuation coefficient in tissues → 5 more times larger penetration depth
 - 5 times larger of Maximum Permissible Exposure (MPE) than at 532 nm → higher optical flux allowable into tissue
 - Response time of GaAs PRC on the order of 1-10 ms or less (depending on the light intensity on PRC).
- sufficient to overcome the speckle decorrelation and is thus suitable for *in-vivo* measurements

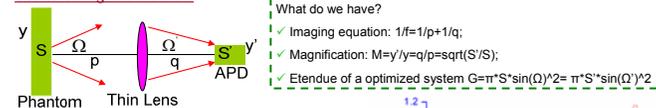
NIR Experimental Setup



Optimization of AOI Imaging setup:

- Maximize scattered light collection after phantom into the PRC
- Maximize the phase shift imparted on the light traveling within diffuse medium by the ultrasound
- Minimize system noise / Maximize signal-noise-ratio (SNR)

Scattered Light Collection:



Experiment I: f, p, q and M fixed, Etendue is changed through change the aperture size of the collecting lens

→ The light collected is almost (not perfect) linear proportional to the Etendue of system (smaller one of the Etendues of light source and photodiode)

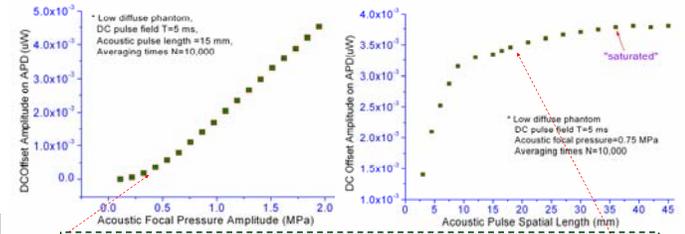
Experiment II: f and Etendue constant, M (p and q) is changed

→ The light intensity collected remains constant

Conclusion: Light collection efficiency is ultimately controlled by the geometric Etendue of the system

Maximize Mean Phase Shift Imparted on the Light by the Ultrasound:

This is controlled by the light/sound interaction strength, which includes interaction volume (acoustic pulse length), ultrasound pressure, ultrasound frequency and ultrasound transducer parameters (numerical aperture, size of focal region), etc. Thus far we have studied the effects of interaction volume and ultrasound focal pressure.



The DC Offset (AOI) signal dependence on focal pressure can be understood as follows: the phase shift imparted on the light is directly proportional to the pressure amplitude. The phase shift is converted to an intensity modulation in the PRC, $I_{DC} \sim J_0(x) - 1 \sim x^2$, where x is the mean value of the phase shift. The maximum pressure amplitude that can be used *in-vivo* is limited by FDA guidelines.

DC Offset initially increases with the pulse spatial length because of the enlargement of AO interaction; When the spatial pulse length exceeds the illumination region, the increase saturates.

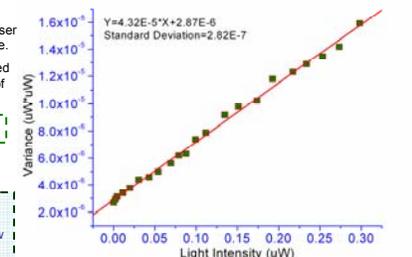
System Noise:

- Potential system noise sources include laser intensity noise, shot noise and thermal noise.
- The RMS value of the noise was measured over a bandwidth of 500KHz as a function of incident light reaching the detector.

Shot Noise $I_s = 2q \times I_{av} \times \Delta f$

→ Shot noise is linearly proportional to the photon flux into the detector

The results indicate that shot noise limited detection achieved for incident light levels greater than approximately 0.06 uW. Below this intensity, thermal noise dominates.



Conclusions

- The spatial resolution of our AO system is determined by ultrasound beam width (radial resolution) and spatial pulse length (axial resolution). → This makes high resolution (sub-millimeter) imaging possible.
- Combining AOI with conventional ultrasound scanners → potentially used for tumor detection and discrimination.
- We can color-code and co-register conventional B-mode images with AO information.
- We can reveal information related to both acoustical and optical properties in diffusive media.
- This research is aimed at optimizing the AOI imaging system and determining the fundamental limitations of this technique. Ultimately it will tell us whether or not Acousto-optic Imaging is technically feasible for transition from a laboratory setting to clinical applications.

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