

Interaction Mechanisms in Acousto-Photonic Imaging

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ABSTRACT

Acousto-photonic imaging (API) is a novel technique for non-invasive medical imaging that combines diffusive optical tomography with externally generated acoustic “virtual” sources to improve the resulting images. We lack, however, a detailed understanding of the nature of the interaction between the diffusive wave and the focused ultrasound. We present our recent theoretical and experimental work on determining the mechanism for the interaction between the acoustic and the optical fields.

Keywords: Diffusive wave, acousto-photonic, imaging, ultrasound modulation

1. INTRODUCTION

Imaging soft tissue within the body has many medically useful applications. Optical techniques are attractive for several reasons: they are safe, non-invasive, the radiation is non-ionizing, and inexpensive LED lasers are readily available. At optical frequencies, though, the body is an extremely challenging medium to image through. While the absorption in the red and near-IR is quite low, scattering lengths (the photon mean free path) are typically on the order of 0.025 mm. By treating the light sources as sources of diffusive photon density waves, it is nevertheless possible to generate medically useful images.

One such technique using diffusive photon density waves is diffusive optical tomography (DOT).¹⁻⁵ By operating at two different wavelengths, DOT exploits differences in the oxy- and deoxy-hemoglobin absorption spectra to simultaneously measure local blood volume and blood oxygenation. Spatial resolution is currently on the order of 1 mm with a maximum optical path around 60 mm. Applications of DOT include tumor screening (in particular, skin and breast cancer), stroke localization, and functional mapping of the brain.

In transmissive geometries where the source and detector fibers are located on opposite sides of the region being imaged, the reconstructed tissue images are quite good. In reflective geometries, however, the reconstructed images suffer from two shortcomings: the reconstructed inhomogeneities consistently have too shallow a depth and too small an amplitude.⁶⁻⁸ Physically, this arises because the majority of photons received by the detector follow a path close to the surface due to the restricted geometry in the reflective configuration. The lower portion of the inhomogeneity, in contrast to the upper portion, is sampled by relatively few photons.

2. ACOUSTO-PHOTONIC IMAGING

One way to improve image quality is to somehow “tag” those photons whose paths take them deep into the tissue. While the actual number of tagged photons may be very small, we can filter out any other photons arriving at the detector. “Tagging” is accomplished using focused ultrasound to modulate the diffusive photon density wave. This technique is known as acousto-photonic imaging (API).⁹⁻¹¹ In acousto-photonic imaging, the focus of the ultrasound acts as a virtual source of photon density waves. Unlike the physical sources, the ultrasound focus is located within the body. By placing these virtual sources inside (or better yet, below) the region of interest, we are able to transform a reflective geometry into something that more closely resembles a transmissive geometry. This can significantly improve the quality of the resulting images.^{8,12}

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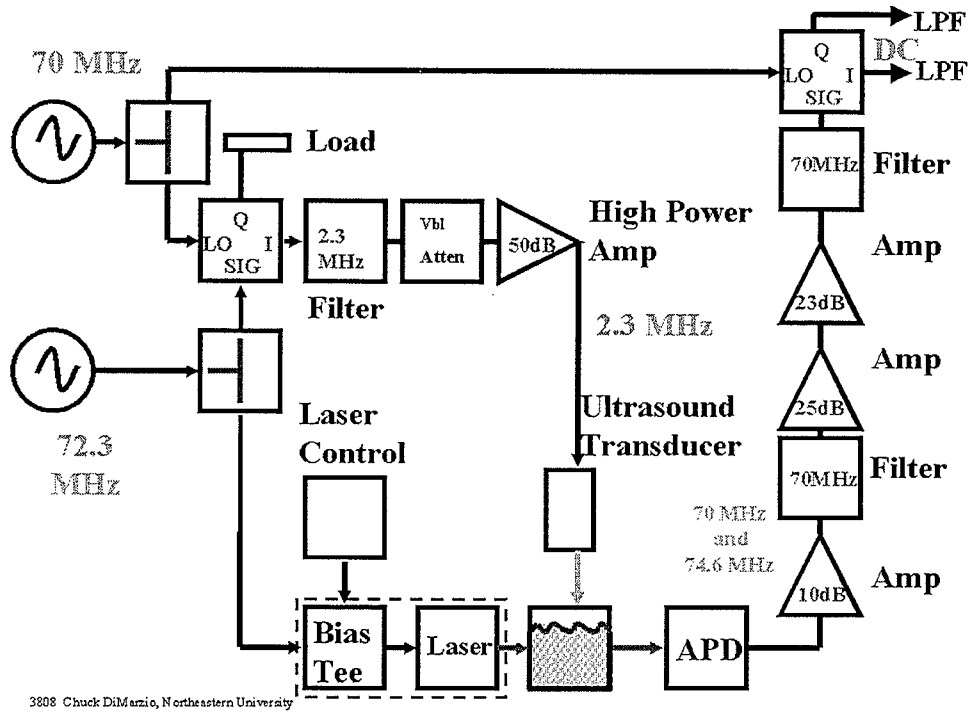


Figure 1. Block diagram of experimental apparatus. The laser light, modulated at 72.3 MHz combines inside the tank with the 2.3 MHz ultrasound signal. The output of the avalanche photo-diode is sent through a bandpass filter centered on 70 MHz which passes only the lower sideband of the acousto-photonic signal. The filtered signal is demodulated using a 70 MHz reference oscillator and the DC component is measured using a digital oscilloscope.

The experimental setup used in our lab is shown in Figure 1. The output of the 72.3 MHz oscillator (an HP 8647A signal generator) is passed through a tee. One side is used to modulate the laser light source (690 nm diode laser operating at 15 mW output power) which is coupled into an optical fiber. The other side of the tee is fed into a demodulator and mixed against a fixed 70 MHz source. The output of the demodulator is sent through a low-pass filter and serves as a 2.3 MHz CW ultrasound source. The laser light and the ultrasound signal combine in the tank. An aqueous suspension of titanium dioxide (TiO_2) provides the scattering. The light is collected by an optical fiber mounted on a two-axis scanner and is fed into an avalanche photodiode (APD) (Hamamatsu C5331-03). The output of the APD is amplified and filtered using a narrow 70 MHz band-pass filter. This removes the signal due to the unmodulated laser light. The signal is then re-amplified and sent into a demodulator where the 70 MHz acousto-photonic signal is mixed against the 70 MHz oscillator. The output of the demodulator is sent through a low-pass filter and the DC level is read off a digital oscilloscope. By moving the detector fiber around the tank, we are able to map out the inphase and quadrature components of the acousto-photonic field. A sample dataset is shown in Figure 2.

3. INTERACTIONS BETWEEN ACOUSTIC AND OPTICAL FIELDS

Based on the work done previously for DOT, we have a reasonably good understanding of the propagation of diffusive waves through uniform highly scattering media.¹⁰ Numerical models, developed by the authors, for the propagation of the acoustically modulated light agree reasonably well with the observed experimental data. The mechanism for the interaction between the acoustic and optical fields, however, are not nearly so well understood. Developing an improved understanding of these interactions is a critical first step in maximizing signal strength.

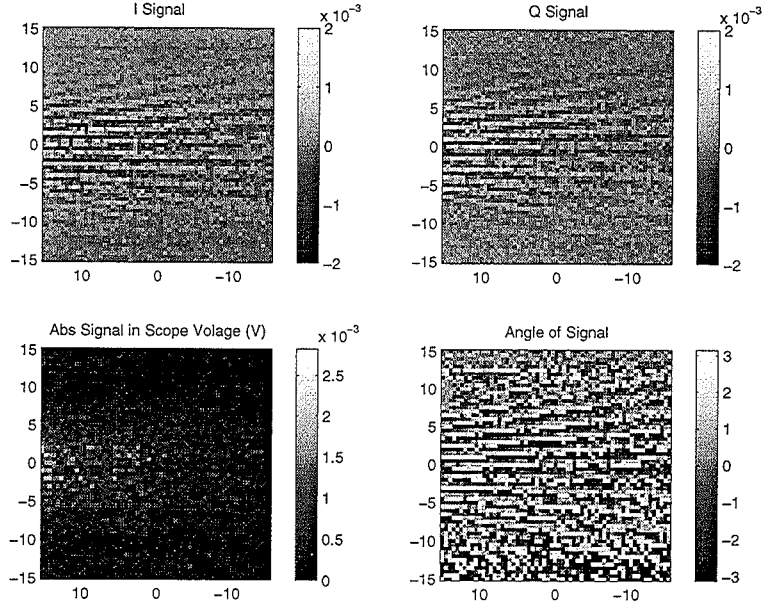


Figure 2. Sample API data. Upper left and right are the inphase and quadrature components of the signal, respectively. Lower left is the signal intensity. Lower right is the phase angle of the signal. The “cone” shape seen in the intensity profile is due to the relatively low concentration of scatter used for this experimental run.

There are two basic types models for the interaction mechanism in API: index of refraction modulations (Raman-Nath effect) and induced particle motion. In index modulation models, the acoustic field compresses the medium and the resulting changes in the index of refraction modulate the light. The modulations in the medium act like a moving diffraction grating and modulate the light at the acoustic frequency. In the particle motion models, the scattering sites are moved by the acoustic field (generally due to the radiation pressure). The speckle pattern of the light changes as the relative particle spacing changes and this appears at the detector as a modulation at the acoustic frequency. Determination of the actual mechanism is more complicated, however, because the viscous drag of the water tends to make index modulations look like particle motion and vice versa.

Initial experiments suggested that the interaction was dominated by index modulations.¹³ More recently, however, *ldots*

4. FUTURE WORK

There are several experiments we intend to perform to help us better understand the details of the interaction between the acoustic and optical fields. As a suspension, TiO_2 tends to settle to the bottom of the tank over time. Thus, the observed scattering lengths tend to decrease from day to day unless more TiO_2 is added to the tank. By using a mixture of surfactants we hope to create a stable tissue phantom and improve the reproducibility of our experiments. Another experiment we would like to make is to increase the viscosity of the TiO_2 suspension (e.g. by adding glycerine to the solution). By varying the viscosity, we should be able to learn about the relative importance of viscous drag versus radiation pressure as an interaction mechanism. Another useful change would be using acrylamide gels impregnated with TiO_2 as an optical scattering agent. These gels are acoustically similar to water, but particle motion will be severely constrained compared to a tank of water due to the properties of the gel. Interactions in gels should be a much more realistic test of acousto-photonic interactions in the body than our current setup. Finally, we would like to modify the experimental setup shown in Figure 1 to use a pulsed ultrasound source. This will permit operation at higher power levels (with corresponding increases in signal intensity) and will minimize the possibility of acoustically generated flows within the tank.

5. CONCLUSIONS

In conclusion, we have demonstrated that acousto-photonic imaging is a useful extension to diffusive optical tomography. While we are getting useful measurements with our current experimental setup, it should be possible to significantly increase our signal strengths by optimizing the acoustic sources. Before we can optimize the sources, we need to significantly improve our understanding of the nature of the interactions between the acoustic and optical fields. ... Thus, while much progress has been made, work remains to be done both theoretically and numerically in modeling the interactions and experimentally in finding appropriate tissue phantoms and optimizing the acousto-photonic signal strength.

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