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Geng Ku, Gang Yao, Lihong V. Wang

Optical Imaging Laboratory, Biomedical Engineering Program
Texas A&M University, College Station, Texas 77843-3120, USA

ABSTRACT

A novel chirped ultrasound-modulated optical tomography technique was developed to image turbid media. Frequency analysis was employed to obtain spatial resolution along the ultrasonic axis. 2D images from scattering medium were obtained. The chirped ultrasound modulated signal was detected in chicken breast tissue.

Keywords: Ultrasonic modulation, frequency swept, optical tomography, turbid media, heterodyne, spectrum.

1. INTRODUCTION

Ultrasound modulated optical tomography is a potential functionally imaging tools for tumor detection in vivo.[1-3] Ultrasound modulated optical tomography combines the relatively transparent ultrasonic radiation with the functional sensitive optical radiation. Based on the study of ultrasound-modulated optical tomography, we developed a novel imaging technique: chirped (frequency-swept) ultrasound modulated optical tomography of turbid media. Instead of single frequency ultrasound, a chirped ultrasonic wave was adopted to add spatial resolution along ultrasonic axis on transmitted laser light. The combination of ultrasound and light allowed us to image objects buried inside turbid media.

Chirp also called frequency sweep which means that the frequency of the ultrasound varies with time as described by

$$f(t) = a + bt$$

where f(t) is the instantaneous frequency of the, a is the starting frequency and b is the sweep rate.

The frequency-swept ultrasound wave propagated vertically along the z axis. If we freeze the time and take a snapshot of the propagating ultrasonic wave, the instantaneous frequency varies linearly along the z axis as shown in Fig. 1. Because the instantaneous frequency of the ultrasonic source increases with time and it takes time for the ultrasound wave to propagate downward, the instantaneous frequency in the snapshot decreases as z increases. In other words, the farther down from the ultrasonic transducer, the lower the instantaneous frequency.

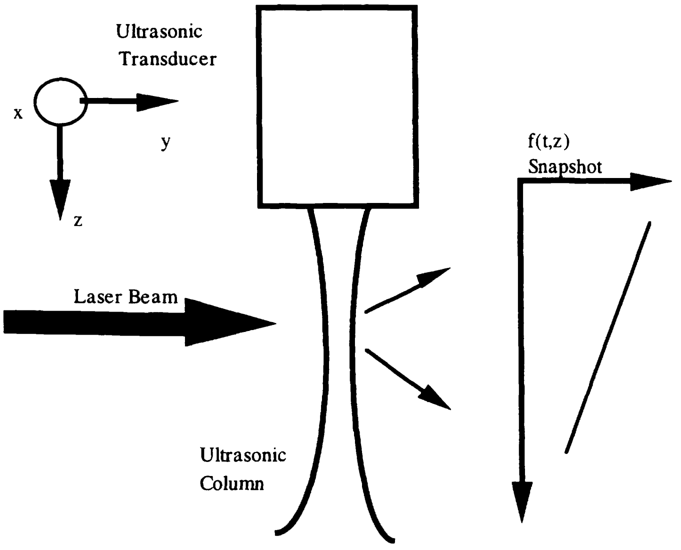


Fig. 1. Instantaneous frequency distribution along the ultrasonic axis (z).

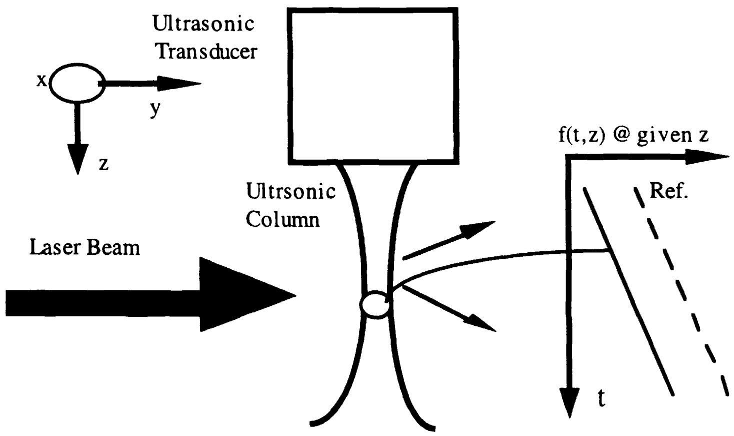


Fig. 2. Instantaneous frequency distribution vs. Time.

Fig 2. shows a frequency distribution vs time of an arbitrary point under ultrasonic axis. The ultrasonic wave propagates vertically along the z axis, passing through this point. The ultrasound frequency at this point varies with time linearly as shown by the solid straight line in Fig. 2. Light at this point is modulated by the frequency along this line. In our experiment, we mixed this signal with a reference modulation signal. The modulation signal was also frequency-swept as shown by the dashed line in Fig. 2. The sweep rate of the reference modulation signal is the same as the signal for the ultrasonic wave but has a different starting frequency. The instantaneous frequency difference between the modulated optical signal at this point and the reference signal is a constant, independent of time. This constant is related to the distance between this point and the ultrasonic transducer. The larger the distance, the greater the constant frequency difference.

Experiment Setup

A block diagram of the experimental setup is shown in Fig. 3. A frequency-swept signal was produced using a function generator and then was amplified in power and amplitude by a power amplifier and a transformer. The amplified signal was applied to an ultrasonic transducer. The ultrasonic transducer converted electric power into acoustic power. The ultrasonic wave propagated vertically into a turbid medium, which was contained in a glass tank. An ultrasound absorber was placed to prevent ultrasonic reflection.

A He-Ne laser beam, at the wavelength of 633nm, after being broadened to 15mm, illuminated the scattering medium perpendicularly to the ultrasound column. The laser source was chirp modulated by another function generator and synchronized to the chirp signal for ultrasound. The two chirps have same frequency sweep rate but different starting frequency. In the ultrasonic column, the intensity chirp modulated light was modulated by chirped ultrasound and caused the heterdyned signal. A photomultiplier tube (PMT) collected some transmitted light and converted the optical power into electric power. The output from PMT interface was band-pass filtered and then amplified using a filter and an amplifier, respectively. The amplified signal was recorded by a digital oscilloscope and then transferred to a computer for post-processing. Lock-in Amplifier was used to detect weak signal.

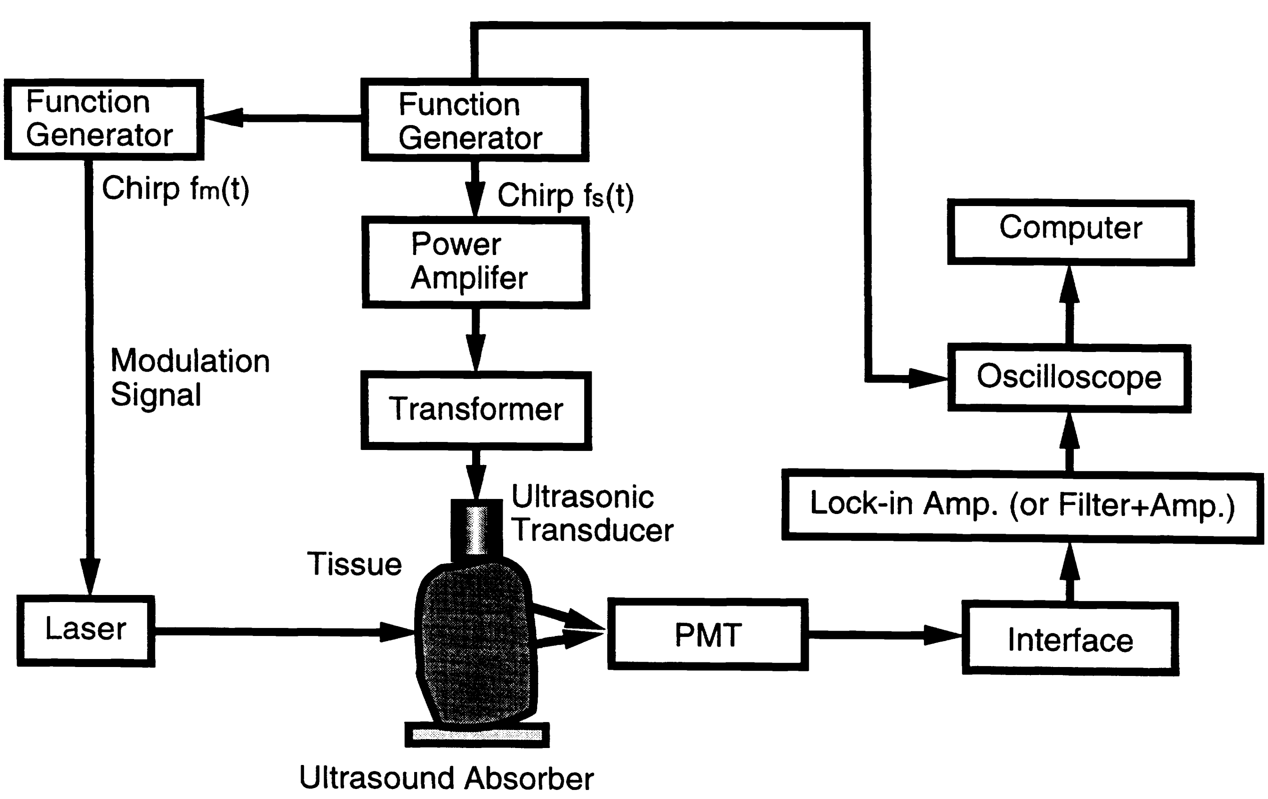


Fig. 3. A block diagram of the experimental setup.

An object was buried in the middle plane of the tank to simulate a tumor. The object was translated in the tank perpendicularly to both the laser beam and the ultrasonic column. A time-domain signal was recorded at each stop. Fast Fourier transform (FFT) was used to obtain the spectra of the recorded time-domain signals.

The frequency spectra yielded imaging information for the zone of interest selected by the band-pass filter. A frequency in the spectra corresponded to the frequency difference between the instantaneous frequency on ultrasonic axial position in the zone of interest and the instantaneous frequency of the modulation signal to the PMT, which was related to the frequency sweep rate and the ultrasonic propagation time. As the time dependent term was erased, the frequency deference was independent of time and was related to the distance between the position on ultrasonic axis and ultrasonic transducer. A frequency in the spectrum was converted into a distance from the transducer surface to a point in the zone of interest. There was a one-to-one correspondence between the frequency in the spectrum and the position in the zone of interest. In other words, a frequency spectrum could be converted into a 1D image of the turbid medium along the ultrasonic axis.

Image and Discussion

A sample 2D image of an object buried in a turbid medium was shown in Fig. 4. The cross section of the object was ~ 6 mm × 2 mm in size. The scattering coefficient and anisotropy of the turbid medium at 633 nm wavelength were 0.21 cm^{-1} and 0.73, respectively. The length of the tank along the laser light was 17 cm.

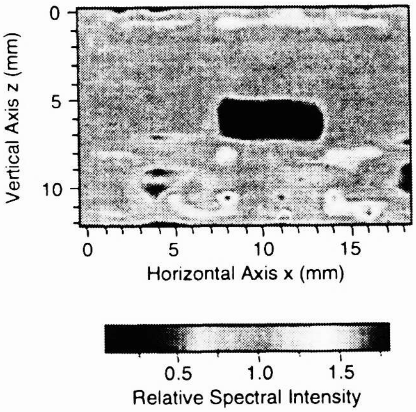
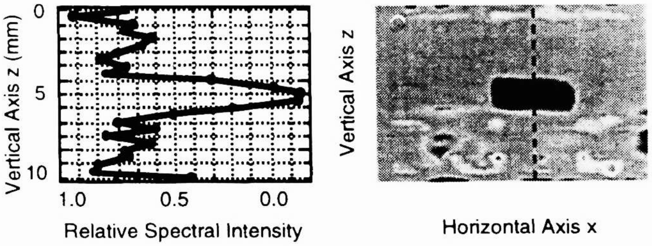


Fig. 4. A 2D tomographic image of an object buried in a turbid medium.

Multiple 1D spectra were acquired while the buried object was scanned horizontally along the x axis with a step size of 1 mm. Each vertical line in this 2D image was obtained from a spectrum. Then, a 2D image of the medium was formed by combining the 1D *relative* spectra taken at the various x positions. The object is clearly visible with a good contrast. The image of the object has a cross section comparable to that of buried object. The location is correct as well.

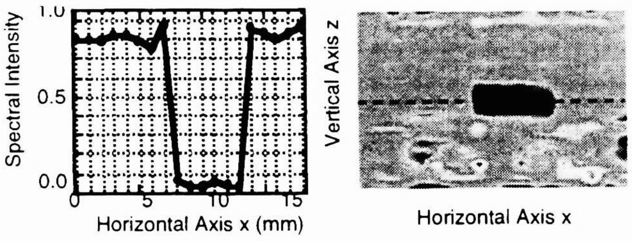
In order to examine the resolution of the image detail, Fig. 5(a) and Fig. 5(b) show the 1D images of the object in scattering medium vertically cross the object and horizontally cross the object respectively. The curve falls or jumps from the noise level to signal level in about 1~1.5 mm. Actually, lateral resolution is determined by focal spot size of the ultrasound. In our experiment, the ultrasonic focal diameter is 0.12 mm. Axial resolution is determined by frequency sweep. We use a chirp swept from 7MHz to 10MHz; The corresponding axial resolution should be 1.5 mm.



1D vertical image

Object in scattering medium

Fig. 5(a). 1D image vertically across the object

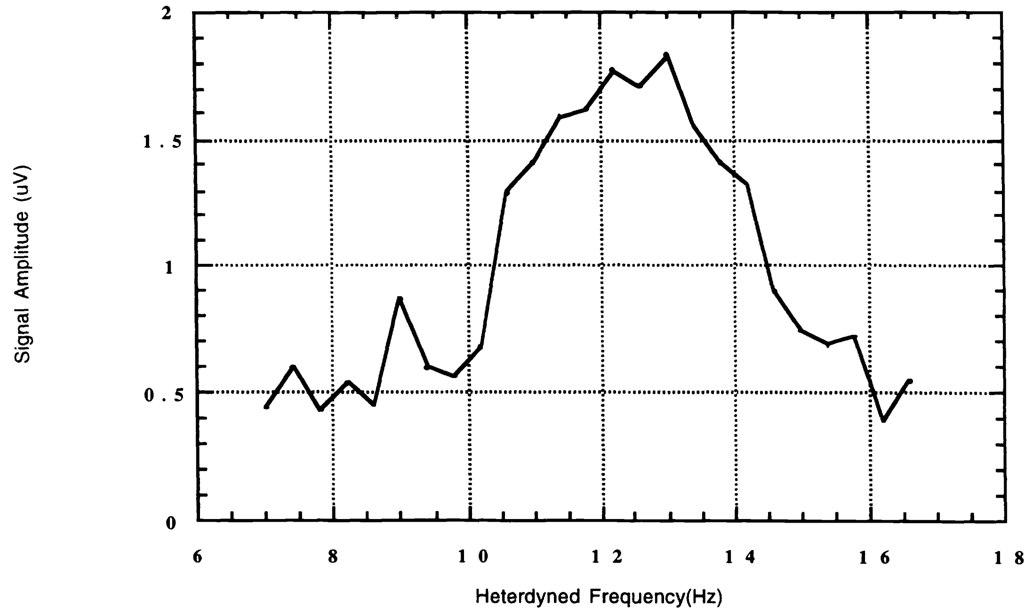


1D Horizontal Image

Object in scattering medium

Fig. 5(b). 1D image horizontally across the object.

The signal of diffuse light from tissue is much weaker than that of ballistic light. We have to use the Lock-in Amplifier to examine the chirp modulated signal. Scan the reference frequency of the Lock-in Amplifier, we get a spectrum as shown in Fig. 6.



Converted the heterdyned frequency spectrum into 1D image. There is modulated signal corresponding to the tissue volume and ultrasonic column.

Conclusion

we have experimentally proved the concept of frequency-swept ultrasound-modulated optical tomography. Image with 1~1.5mm resolution was obtained. The resolution is scaleable with frequency sweep and ultrasonic focal spot size respectively. 1D image was obtained with a single time domain signal. 1D scanning cross a object gives the image of the cross section of the object. The chirp modulated signal from the chicken tissue was also detected.

Acknowledgment

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