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LASER APPLICATIONS AND OTHER TOPICS IN QUANTUM ELECTRONICS

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Acousto-optic tomography using amplitude-modulated focused ultrasound and a near-IR laser

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Abstract. **A novel tomographic method that can be applied in strongly scattering optical media is proposed. 1-MHz focused ultrasound is used to tag the scattering photons in the biological tissue; it carries a 10-KHz sinusoidal wave to act as a detection wave through amplitude-modulation (AM). The scattering photons that come from the focused zone carry the modulated information. Their opto-electronic signal is demodulated by real-time FFT. By detecting and discriminating ultrasound-modulated information carried by scattered photons, the optical tomographic images of the media simulating biological tissue and of a buried object are reconstructed by the AM spectral intensity. This ultrasound-tagged optical tomography can be applied to tissue structures with different optical parameters. For the first time, by using this method, we obtained the tomographic image of a 5 mm-wide soft rubber cube buried in a biological tissue-simulating media with a detecting depth of 30 mm.**

Keywords: *optical tomography, ultrasound, medicine.*

1. Introduction

Diagnosis of cancerous tumors of parenchyma organs in the initial stages of growth is very important for the clinical treatment of cancer. The present morphological methods, such as nuclear magnetic resonance and X-ray tomography, not only cause radiation insult to the human body in some degree, but also require the use of expensive equipment. Little harm is caused by ultrasonography and the equipment is cheaper. However, it is impossible to perform tomography using this process because its imaging principle depends on the ultrasound reflection from the tissue interface. In addition, ultrasound examination cannot provide the desired image accuracy. With ultrasonography, the best result is a millimeter resolution for simple structure biological tissue, and the resolution deteriorates when examining moving organs. Because of these disadvantages the clinical application of these morphological methods is restricted.

In order to overcome these shortcomings and to provide more effective diagnostic methods, new tomography technologies are being developed. Optical tomography of biological tissues has become an active research field because of the advantages of noninvasive and functional imaging for biomedical diagnosis. However, it is very difficult to image thick tissue by the pure optical method because biological tissues are optically turbid and strongly scattering. Although it is possible to image at depths of several centimeters, using some noncoherent measurement methods [1 – 3], the image resolution is not adequate. The coherent optical tomography can provide high-resolution images, but it is limited by a penetration depth of several millimeters into biological tissues [4 – 5].

For imaging tissue in depth, ultrasound-modulated optical tomography has been developed by combining the advantages of ultrasound and optical technology [5 – 7]. Because ultrasonic waves scatter much weaker in biological tissue than light waves, it can be used as a localizer in tissue. The centimeter depth tomography in simulating media has been achieved, its resolution of two-dimensional images being about several millimeters. Therefore this method is promising for imaging thick biological tissues.

Generally speaking, the signal-to-noise ratio (SNR) is very low in this combined method. The tagged photon signal was weaker than background noise, and only a small part of the scattered photons passes through the ultrasonic focused zone and is modulated. This is mainly due to the following three factors. First, the small size of the ultrasonic focused zone is necessary to obtain high-resolution tomographic image. Second, ultrasonic power density must be kept below the damage threshold of the biological tissue; this restricts the ability to increase the ultrasonic modulation ratio in the focus area by increasing the ultrasonic power density. Third, a small detector aperture is necessary to observe the scattered instantaneous image of optical speckle. It is very difficult to discriminate and measure the modulated signal under this very low SNR condition. Consequently, improving SNR and measurement accuracy is the key to increasing the detection sensitivity and imaging contrast.

In this paper, scattered light signal modulated by an amplitude-modulated (AM) ultrasonic wave is utilised for the first time to perform tomography of a buried object (simulating abnormal tissues) in a medium simulating biological tissue. 1-MHz frequency focused ultrasound, which is similar to the carrier in microwave communication, is modulated in amplitude by a 10-kHz detecting wave, which is

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similar to the signal wave in microwave communication. The modulated light signal is discriminated and demodulated by real-time Fast Fourier Transform (FFT). It improves the processing speed and measurement accuracy. We have reconstructed a tomographic image of a buried object in a simulating medium, and both the resolution and contrast of the image were better than those in previous work [5].

2. Experimental setup and methods

Fig. 1 shows a diagram of the experimental setup. The experiment system included the following parts.

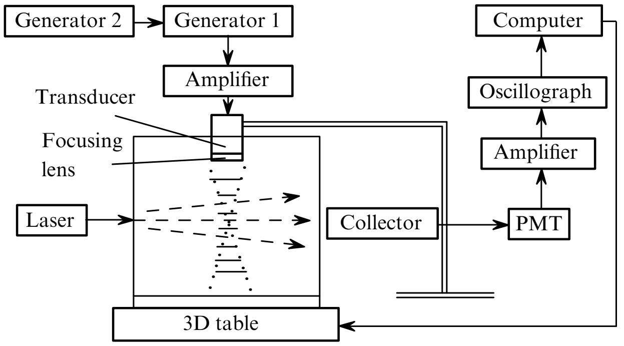

Figure 1. Schematic of the experimental setup

2.1 Sample cuvette and a medium simulating biological tissue.

The sample cuvette was made of methyl methacrylate rectangular plates, which were coated with a material absorbing ultrasound and light. The cuvette had two quartz glass windows 40 mm × 40 mm in size. The distance between the windows was 60 mm. The cuvette was placed on the 3D translation stage which was controlled by a computer. The cuvette contained a biological medium simulating a tissue and a small soft rubber object simulating an abnormal tissue. The former is background liquid tissue phantoms; it is a strong scattering media compounded with dissolved Trypan Blue dye (Sigma, T-6146), Intralipid (Huarui Company, 20 %) and water to simulate the optical properties of tissue [5]. The absorption coefficient μ_a and reduced scattering coefficient μ_s of the simulating turbid medium are controlled to 0.1 cm^{-1} and 10 cm^{-1}, respectively, which are close to the corresponding parameters of red color light in biological tissue [5, 8]. The latter, as the detected buried object, is a 5mm-wide cube, its μ_a and μ_s are 1.7 cm^{-1} and 12.2 cm^{-1}, respectively. The cube was placed in the middle of the cuvette, its sides being parallel to those of the cuvette.

2.2 Ultrasound

Signal generator 1 (Tektronix, AFG320) produced a 1-MHz cw sinusoidal wave at the resonance frequency of the ultrasonic transducer. Signal generator 2 (Nanjing, EE1642B) provided a 10-KHz sinusoidal wave used for the amplitude modulation, the signal was fed to AFG320 through its AM input channel. The output signal of AFG320 is an amplitude-modulated signal, which is amplified by a power amplifier (ENI, 2100L) to drive the transducer. The modulation depth of the ultrasonic carrier frequency is approximately 0.8. Both the signal intensity and its stability are optimised at this value. The ultrasonic transducer's active element (piezoelectric ceramic) is 32 mm in diameter. An ultrasonic lens is clamped together with ultrasonic output surface of the transducer to focus the ultrasonic wave. Its focal length is 34 mm and focal zone diameter is about 2 mm.

2.3 Laser and signal processing system

We used a Ti:sapphire ring laser (Coherent, 899), which provides high-quality cw radiation tunable within a broad spectral range. In our experiments, we used a 15-mW, 860-nm laser line for the scan and measurements. The direction of the laser beam was perpendicular to the ultrasonic beam.

The scattered light was collected by a fibre optic collector, and then transmitted to a low temperature cooled photomultiplier tube (PMT, Hamamatsu, R955). The output signal of the PMT was amplified by a low-noise amplifier and then fed to a digital oscilloscope (TDS3032, Tektronix), which had a FFT module. The time-domain signal waveforms were transformed to their frequency spectrum in real-time and transmitted to the computer. The spectral intensity of the optical signal at each scanning position was recorded with a personal computer. The computer controlled the movement of the 3D translating stage during the scan.

3. Results and Discussion

The characteristics of modulated photons are related to the mechanical and optical properties of the biological tissue in the position where photons were modulated. Therefore, the

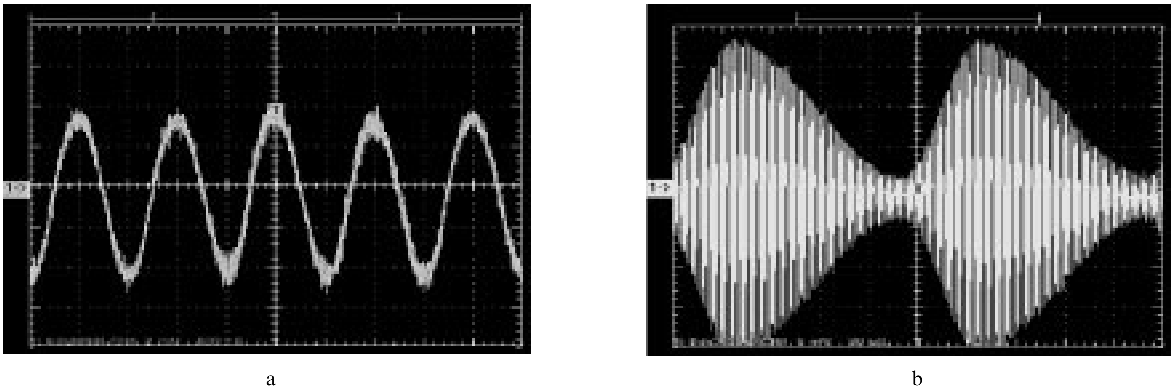

Figure 2. Ultrasonic modulated optical signal in a simulating medium, (a) modulated by 1-MHz ultrasound (scale: 2 mV/500 ns), (b) AM ultrasonic modulated optical signal, 1-MHz ultrasonic frequency and 10-KHz AM frequency (scale: 5 mV/40 μs).

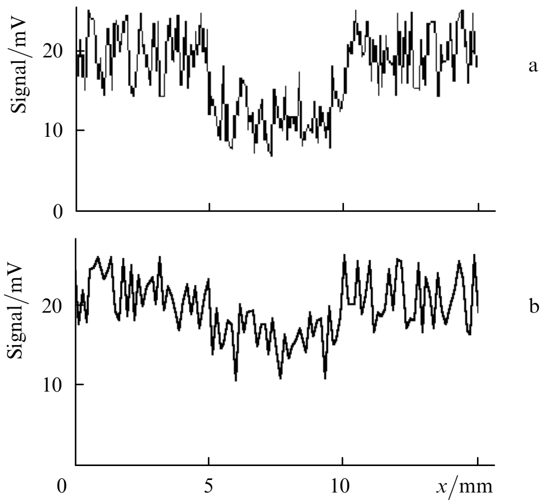

Figure 3. 1D scan image with a 0.1-mm scanning step over *x* axis with (a) and without (b) amplitude modulation.

measurements of modulated photons can reveal the difference in the structure and functions of biological tissues. The signal provided by PMT consists of DC and AC components. The ratio of the AC signal amplitude to the DC signal is in the range of $1:10^5$ to $1:10^6$, which is the modulation depth.

This value is so small because the biological tissue is a strongly scattering medium (the incident laser radiation is strongly scattered in the biological tissue), and the ultrasonic focal zone is very small (only a few photons pass through the focal zone and are modulated). Modulated photons, emerging from the region of focused ultrasound, fluctuate under the action of optical and mechanical parameters of the medium, especially μ_a and μ_s. During scan, region of focused ultrasound passes through object and the background medium. The buried object can be distinguished from the background by the variation of the optical signal.

The 1-MHz ultrasonic modulation signal and 10-KHz AM modulation signal were separated from background and noise by FFT. Fig. 2a shows the optical signal modulated by 1-MHz ultrasound, Fig. 2b shows optical signals modulated at 1 MHz and 10 KHz.

In the experiment, the time-domain signals were transformed to specral signals by the FFT module in real time, and the spectral intensity of the signal was measured directly. The measurement of the spectral intensity improves the accuracy compared to the peak-to-peak measurements of the signal voltage. More valuable information, such as the interaction between the light and the tissue, may be obtained in the frequency-domain signal. It would be helpful

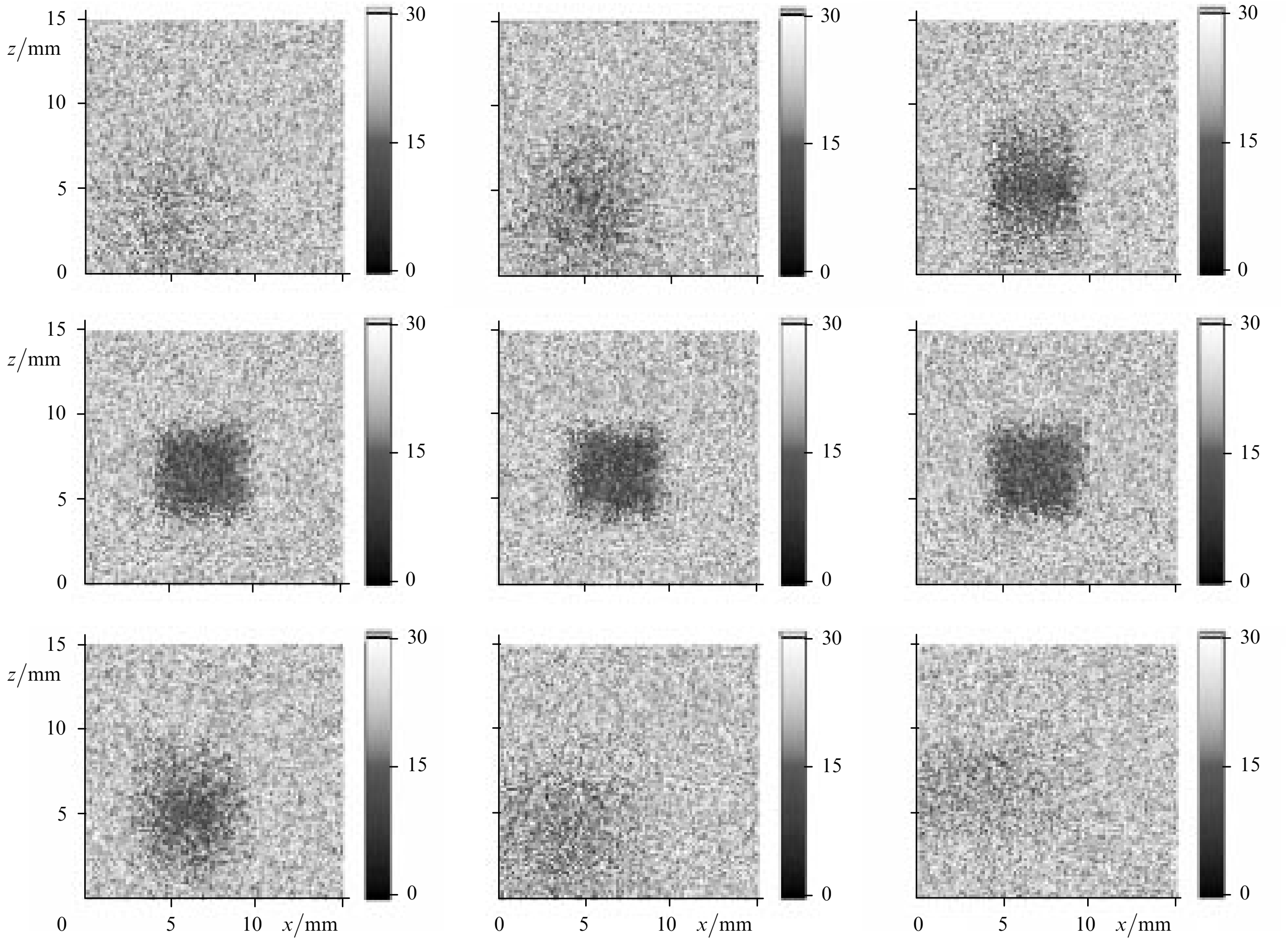

Figure 4. A set of 2D tomographic images of the object buried in a simulating medium (coordinate unit: mm). The signals were collected with a lateral resolution of 0.1mm. The images (a), (b), (c), (d), (e), (f), (g), (h), and (i) are collected with longitudinal scanning over buried object with a 1.5-mm step, respectively.

to study further the mechanism of interaction between a photon, ultrasound and tissues.

Fig. 3a shows a one-dimensional distribution of the AM signal spectral intensity in the horizontal axis. For comparison, we present another one-dimensional scan result, shown as Fig. 3b and obtained without the amplitude modulation. The contrast and edge resolution of the former is better than those for latter. The spectral intensity of the detection wave, which was loaded on the 1-MHz ultrasonic wave, is obviously varied. The reason is due to the difference of mechanical and optical properties between the buried body and its background, which results in different reactivity to the ultrasound-modulated frequency. The detailed mechanism needs to be studied further.

Upon scanning the simulating medium by moving the translation stage along x axis, the one-dimensional image at the horizontal direction can be obtained. By scanning along both x axis and z axis (vertical direction), we can obtain the two-dimensional distribution of the signal spectral intensity and reconstruct a tomographic image of the buried cube in dense turbid media. If step is made along the optical axis direction and the 2D scanning is repeated, a 3D tomographic image of buried objects can be obtained.

Fig. 4 shows a set of 2D tomographic image of simulating media and buried object. The object is soft rubber cube, 5 mm × 5 mm × 5 mm in size, placed in the middle of a 60 mm-wide cuvette. The tomographic planes are perpendicular to the laser beam. The object is clearly seen and its boundary is distinct. The edge resolution is approximately 1 mm, better than in previous work [5], where the resolution was 2 mm.

4. Conclusions

A novel method of ultrasound-modulated optical tomography was proposed, in which the ultrasonic-wave amplitude was modulated to increase the detection sensitivity and the signal-to-noise ratio. The modulated light signal is demodulated by FFT in real time and the tomographic image is reconstructed with frequency-domain spectral intensity. We obtained a 2-D tomographic image of the object buried in the medium stimulating a biological tissue at a 30 mm depth. The resolution and contrast of the image can be further improved by reducing the size of the focal zone area using multi-element phase controlled technology. It is possible to develop this method for the practical use, which has a tremendous potential in clinical applications.

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