

# Experimental study of ultrasound-modulated scattering light using different frequencies ultrasound probes

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The focused ultrasound plays a role in localization and modulating the scattering light in ultrasound-modulated optical tomography (UOT). Both the modulation efficiency of the scattering light and the spatial resolution of UOT are determined by ultrasound. The effects of repetition frequency and pulse energy of impulse ultrasound on the modulated scattering light are derived through experiment in this letter. Furthermore, we compare the imaging sensitivity with 1, 2.25, 5, and 10 MHz center frequencies of impulse ultrasound. Experimental results demonstrate that better signal-to-noise ratios and higher sensitivities can be gained by use of more intense ultrasound and lower ultrasound frequencies.

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Ultrasound-modulated optical tomography (UOT)<sup>[1–3]</sup> is one of acousto-optic interaction imagings. The focused ultrasound plays a role in localization and modulating the scattering light in UOT. It is closely related to the modulation efficiency of scattering light and determines the spatial resolution of UOT. Kim *et al.* used intense acoustic bursts to enhance the ultrasound-modulated optical signals and improve signal to noise ratio (SNR)<sup>[4]</sup>. Lesaffre *et al.* obtained a millimetric axial resolution by applying random phase jumps on continuous ultrasound and light<sup>[5]</sup>. Using a long-cavity confocal Fabry-Ferrot interferometer and 15-MHz ultrasound, Sakadzic *et al.* imaged with high resolution light-absorbing structures placed > 3 mm below the surface of chicken breast tissue<sup>[6]</sup>. The resolution along the axial and the lateral directions were better than 70 and 120  $\mu\text{m}$ , respectively<sup>[6]</sup>. Kothapalli *et al.* used a high-frequency focused ultrasound with a 75-MHz central frequency and achieved an imaging depth of about 2-mm-depth tissue mimicking phantoms, whose resolution was better than 30  $\mu\text{m}$ <sup>[7]</sup>.

In this letter, we study the effect of repetition frequency and pulse energy of impulse ultrasound on the modulated scattering light through experiment. Furthermore, we compare the imaging sensitivity with 1, 2.25, 5, and 10 MHz center frequencies of impulse ultrasound. Based on the experimental results, an appropriate parameter of ultrasonic probe is chosen to enhance the SNR and sensitivity of the imaging system.

The experimental setup is shown in Fig. 1. A 632.8-nm He-Ne laser (CVI Melles Griot, 25-LHR-925-230) is shone on the sample. The laser light is a beam of 1-mm-diameter parallel light and has a maximum power of 22 mW. The sample is the 1-cm-thick intralipid solutions (scattering coefficient: 13.8  $\text{cm}^{-1}$ ). We can change the scattering and absorption coefficients of the sample by adding different levels of intralipid and ink into sample. Along the vertical optical axis, the ultrasonic pulser-receiver (Panametric 5800PR) drives four different types

of ultrasonic transducer (Panametric A314S, A305S, A308S, and A315S) to generate separately pulsed ultrasound with 1, 2.25, 5, and 10 MHz center frequencies on the sample, respectively. The repetition frequency and pulse energy of pulsed ultrasound are variable. The ultrasound travel direction ( $y$  axis) is perpendicular to the optical axis ( $z$  axis). The ultrasonic focal area falls on the optical axis due to its largest intensity, thus having the incident lights passing through the ultrasonic focal area to gain larger optical signals modulated by ultrasonic wave. Two tiny holes with 1-mm diameter are put between the sample and the photomultiplier (PMT). These two holes enable the PMT to easily detect evident ultrasonic modulation signals. The finally detected ultrasound-modulated laser light signals are displayed on the oscilloscope (TDS3054C) after amplified through the amplifier (C6438). The average and the peak-to-peak values of the ultrasound-modulated light signal displayed on the oscilloscope are defined as the intensity of transmitted beam ( $I_{\text{dc}}$ ) and modulated light intensity ( $I_{\text{ac}}$ ), respectively. Dividing the half  $I_{\text{ac}}$  by the  $I_{\text{dc}}$  is the modulation depth ( $M$ ).

Figures 2(a)–(d) show the signal waveform and the frequency spectrum of ultrasound-modulated light and pulsed ultrasonic wave, respectively. Four types of

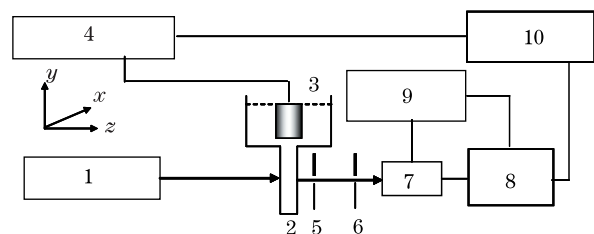


Fig. 1. Experimental setup: 1 He-Ne laser; 2 water tank; 3 ultrasonic transducer; 4 ultrasonic pulser-receiver; 5 the second aperture; 6 the first aperture; 7 PMT; 8 amplifier; 9 multipurpose power supply (C3830); 10 oscilloscope.

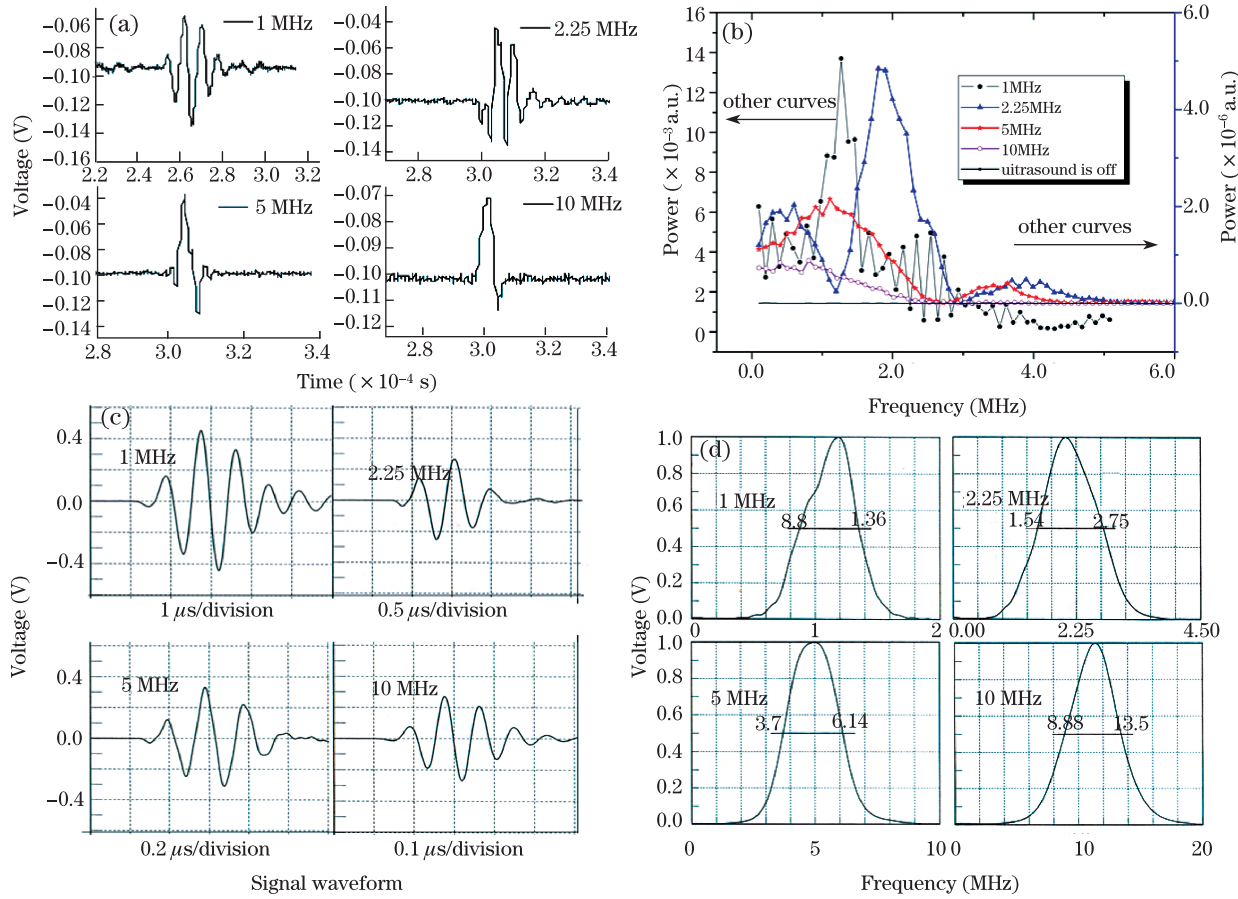


Fig. 2. (a) Signal waveform and (b) frequency spectrum of ultrasound-modulated light. (c) Signal waveform and (d) frequency spectrum of pulsed ultrasonic wave.

ultrasonic transducer were used in the experiment. The center frequencies of the pulsed ultrasound are 1, 2.25, 5, and 10 MHz, respectively. The zero frequency is removed from the spectrum of the ultrasound-modulated light in Figs. 2(b), because the zero frequency intensity represents the unmodulated light signal which is not the scope of our study. As shown in Fig. 2(a) and (c), the ultrasound-modulated light signal is not similar to the pulsed ultrasonic wave except the 1-MHz pulsed ultrasonic wave. In Fig. 2(b), the detected lights modulated by 1-MHz pulsed ultrasonic wave have significantly greater spectral intensity within 0.5–1.5 MHz frequency range than those under no ultrasonic effect, which finds good accordance with the spectral range of pulsed ultrasound (Fig. 2(d)). When 2.25, 5, and 10 MHz pulsed ultrasounds are used, the spectrum of ultrasound-modulated light amassed almost in the range of 0–3 MHz. What's more, the maximum spectral intensity ( $\sim 0.014$ ) of 1 MHz ultrasound-modulated light is three orders of magnitude larger than those modulated by 2.25, 5, and 10 MHz pulsed ultrasounds. It is thus clear that a higher modulation efficiency of scattering light can be gained by use of lower ultrasound frequencies. In another paper (submitted), an analytic equation interpreting that the intensity of scattering light modulated by ultrasound is derived based on the diffusion theory. Take the simplest one-dimensional space for example. Such one-dimensional space is equal to the mod-

ulated light intensity detected by  $Z$  axis (optical axis) when a wide beam of standard parallel lights shoots into the semi-infinite scattering medium. The scattering light intensity in the medium modulated by ultrasonic field is

$$I(z, t) \propto A(z) \exp\left(-B \frac{P_m}{\omega_a} \cos \omega_a t\right), \quad (1)$$

where  $A(z)$  and  $B$  are the coefficients determined by the optical properties of medium,  $\omega_a$  is the radian frequency of ultrasound, and  $p_m$  is the amplitude of acoustic pressure. Equation (1) shows that the variation amplitude of the modulation light signals, i.e. modulation efficiency, is proportional to the amplitude of acoustic pressure ( $P_m$ ) and inversely proportional to acoustic angular frequency  $\omega_a$ . The result of the experiment is in accordance with the theoretical prediction in this letter.

A 1-MHz pulsed ultrasonic wave was used in the experiment and the pulse energy of ultrasound was  $100 \mu\text{J}$ . The effect of the repetition frequency of ultrasound on ultrasound-modulated light is shown in Fig. 3. Fig. 3 shows that  $I_{dc}$ ,  $I_{ac}$ , and  $M$  are nearly unchanged with the increase of the repetition frequency of ultrasound. So the different pulse repeating frequencies of ultrasound have little influence on the modulated scattering light.

The repetition frequency of 1-MHz pulsed ultrasonic wave is 10 kHz. The relationship between the ultrasound-modulated light and the ultrasonic energy is shown in

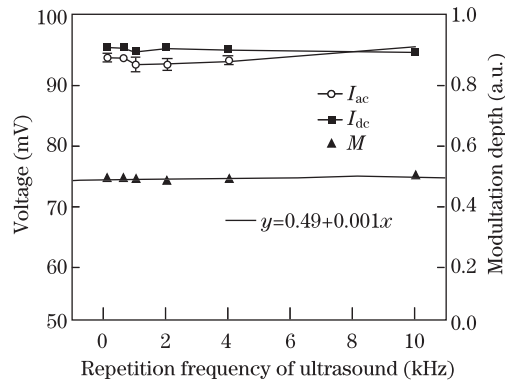


Fig. 3. Ultrasound-modulated light signal versus the repetition frequency of ultrasound.

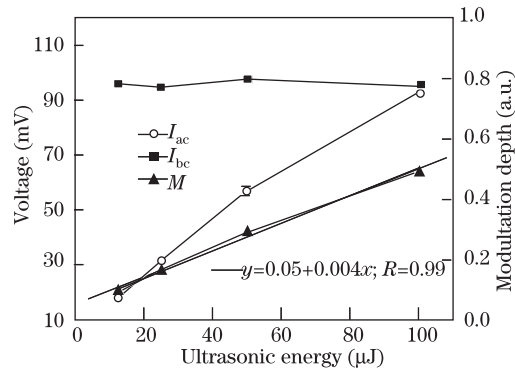


Fig. 4. Ultrasound-modulated light signal versus the ultrasonic energy.

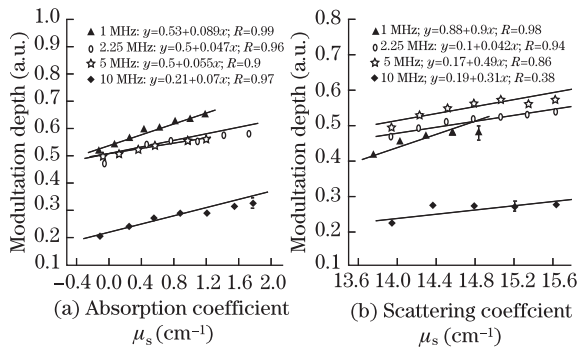


Fig. 5. Ultrasound-modulated light signal versus (a) the absorption coefficient and (b) the scattering coefficient of the medium.

Fig. 4. The experimental results (Fig. 4) demonstrate that  $I_{ac}$  and  $M$  increase linearly with the increase of the ultrasonic energy, and  $I_{dc}$  only changes slightly.  $M$  increases by 0.004 for every  $1 \mu\text{J}$  increase of ultrasonic energy. Therefore, increasing ultrasonic energy is a very efficient method for improving modulation efficiency and signal-to-noise ratios.

The imaging sensitivities with 1, 2.25, 5, and 10 MHz center frequencies of impulse ultrasound are compared. The repetition frequency is 10-kHz and the pulse energy is  $100 \mu\text{J}$ . Because the effect of the detection location of

PMT on the modulation depth is great<sup>[8]</sup>, we keep PMT at the same detection location to study the relationship between the modulation depth and the absorption coefficient and scattering coefficient of the medium. As shown in Fig. 5, modulation depth ( $M$ ) increases linearly with the increase of the absorption coefficient and scattering coefficient of the medium.  $M$  increases by 0.09 for every  $1 \text{ cm}^{-1}$  increase of absorption coefficient and scattering coefficient when a 1-MHz pulsed ultrasonic wave is used. When a higher frequency ultrasonic wave (such as 2.2 and 5 MHz) is used, the slopes of  $M$  are only about 0.05. Especially when a 10-MHz is used, the modulation depth is less (0.2–0.3) and the slopes of  $M$  are about 0.03, as shown in Fig. 5(b). It is evident that the sensitivity is higher with 1 MHz ultrasound than with 2.25, 5, and 10 MHz ultrasounds respectively.

In conclusion, we use focused ultrasound of various frequencies on the scattering medium respectively, and have the incident lights passing through the ultrasonic focal area to gain optical signals for ultrasonic modulation by PMT. The effects of repetition frequency and pulse energy of impulse ultrasound on the ultrasonic modulation of scattering light are derived through experiment. Furthermore, we compare the imaging sensitivities in UOT with 1, 2.25, 5, and 10 MHz center frequencies of impulse ultrasound. Experimental results demonstrate that the modulation efficiency increases with the increase of the pulse energy of ultrasound. And the different pulse repeating frequencies of ultrasound have little effect on the modulated scattering light. The sensitivity is higher with 1 MHz ultrasound than that with 2.25, 5, and 10 MHz ultrasounds respectively. The experimental results provided the basis for choosing an appropriate parameter of ultrasonic probe to enhance the SNR and sensitivity of UOT.

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