Theoretical Analysis for Conversion Efficiency of Laser Generation of Acoustic Waves in Liquid

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***Abstract*—In order to implement laser generation of acoustic waves in liquid efficiently, the optical-acoustic conversion efficiency was calculated and its influenced factors were analyzed, such as, time-domain power distribution, peak power density and pulse width of laser, and optical absorption coefficient of fluid medium. The theoretical analysis shows that: the larger the peak power density is, the larger the conversion efficiency will be; The growth rate of conversion efficiency of Gaussian pulse laser generation of acoustic waves is the largest; With the increasing of optical absorption coefficient or pulse width, the optical-acoustic conversion efficiency can reach a maximum value; Under the same conditions, comparing with triangle and Gaussian laser pulse, the optical-acoustic conversion efficiency is the largest when the power distribution of pulse laser is sinusoid function waveform.**

Keywords—underwater acoustics; laser generation of acoustic waves; conversion efficiency;

I. INTRODUCTION

Sound source is one of the key devices of underwater acoustic communication. Photoacoustic source is a type of novel acoustic source in liquid. Laser generation of acoustic waves in liquid has attracted more attention due to its excellent properties, such as coupling with the sound bearing medium around photoacoustic source, coving extensive water area, maneuverability, non-contact with fluid medium, the ability to be used under various harsh conditions and so on [1].

When light from a laser beam passes through liquid, several physical mechanisms can lead to the generation of sound: thermoacoustic or thermoelastic, vaporization, optical breakdown, etc. The thermoelastic mechanism is thought to be common. The theory of thermoelastic sound generation has been reported [2]. We also need to know the characteristics of photoacoustic source generated by pulse laser of different time-domain power distributions and the optical-acoustic conversion efficiency during the process. To implement laser generation of acoustic waves efficiently, it is necessary to analyze optical-acoustic conversion efficiency. In this paper, a theoretical model for laser generation of acoustic source is established and the optical-acoustic conversion efficiency and its influenced factors are analyzed.

II. THEORETICAL MODEL FOR LASER GENERATION OF ACOUSTIC SOURCE

In the mechanism of thermal expansion, the portion of the liquids absorbing pulse laser energy is instantaneously heated. If the absorption of laser energy is not enough to cause a phase change, instantaneous thermal expansion of volume in the heated medium will produce a photoacoustic pulse. The formation of photoacoustic wave can be described by the following pressure wave equation [3].

$$\nabla^2 P - \frac{1}{{c_0}^2}\frac{\partial^2 P}{\partial t^2} = -\frac{\beta}{C_P}\frac{\partial H}{\partial t} \tag{1}$$

Where P is acoustic pressure; β is volume expansion coefficient of liquid, $\beta = -\frac{1}{\rho_0}\left(\frac{\partial \rho_0}{\partial T}\right)_P$;T is temperature, assuming constant during the entire process; C_P is specific heat at constant pressure; $H(x,y,z,t)$ is a function defined as the heat deposited in the medium per unit volume and time; and t is time.

Through theoretical derivation, the analytical solutions of photoacoustic pulses generated by a sinusoid laser pulse, a triangle laser pulse, and a Gaussian laser pulse can be given by the following equations respectively:

$$P_S\left(\tilde{\theta}\right) = \begin{cases} \dfrac{\pi\beta I_0 A^3 e^{A\tilde{\theta}}\left(e^{-A}+e^{A}\right)}{2\alpha^2 c_0 C_P \tau_L t_0\left(A^2+\dfrac{\pi^2}{4}\right)} & \tilde{\theta} < -1 \\ \dfrac{\pi\beta I_0 A^3}{\alpha^2 c_0 C_P \tau_L t_0\left(A^2+\dfrac{\pi^2}{4}\right)}\left[-\sin\left(\dfrac{\pi}{2}\tilde{\theta}\right)+\dfrac{1}{2}e^{-A}\left(e^{A\tilde{\theta}}-e^{-A\tilde{\theta}}\right)\right] & -1 \le \tilde{\theta} \le 1 \\ -\dfrac{\pi\beta I_0 A^3 e^{-A\tilde{\theta}}\left(e^{A}+e^{-A}\right)}{2\alpha^2 c_0 C_P \tau_L t_0\left(A^2+\dfrac{\pi^2}{4}\right)} & \tilde{\theta} > 1 \end{cases} \tag{2}$$

$$P_T\left(\tilde{\theta}\right) = \begin{cases} \dfrac{\beta I_0 A e^{A\tilde{\theta}}}{\alpha^2 c_0 C_P \tau_L t_0}\left(e^{A}+e^{-A}-2\right) & \tilde{\theta} < -1 \\ \dfrac{\beta I_0 A}{\alpha^2 c_0 C_P \tau_L t_0}\left[2-2e^{A\tilde{\theta}}+e^{-A}\left(e^{A\tilde{\theta}}-e^{-A\tilde{\theta}}\right)\right] & -1 \le \tilde{\theta} \le 0 \\ \dfrac{\beta I_0 A}{\alpha^2 c_0 C_P \tau_L t_0}\left[-2+2e^{-A\tilde{\theta}}+e^{-A}\left(e^{A\tilde{\theta}}-e^{-A\tilde{\theta}}\right)\right] & 0 < \tilde{\theta} \le 1 \\ -\dfrac{\beta I_0 A e^{-A\tilde{\theta}}}{\alpha^2 c_0 C_P \tau_L t_0}\left(e^{A}+e^{-A}-2\right) & \tilde{\theta} > 1 \end{cases} \tag{3}$$

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$$P_G\left(\tilde{\theta}\right)=\begin{cases}\dfrac{\sqrt{\pi}\beta I_0A^3}{2\alpha^2c_0C_Pt_0{}^2}\left[erf\left(\dfrac{t_0}{2\tau_l}+\dfrac{A\tau_l}{t_0}\right)-erf\left(-\dfrac{t_0}{2\tau_l}+\dfrac{A\tau_l}{t_0}\right)\right]\exp\left[\left(\dfrac{A\tau_l}{t_0}\right)^2+A\tilde{\theta}\right] & \tilde{\theta}<-1\\ \dfrac{\sqrt{\pi}\beta I_0A^2}{2\alpha^2c_0C_Pt_0{}^2}\left\{\begin{array}{l}\exp\left[\left(\dfrac{A\tau_l}{t_0}\right)^2-A\tilde{\theta}\right]\left\{\begin{array}{l}-A\left[erf\left(\dfrac{t_0\tilde{\theta}}{2\tau_l}-\dfrac{A\tau_l}{t_0}\right)+erf\left(\dfrac{t_0}{2\tau_l}+\dfrac{A\tau_l}{t_0}\right)\right]+\\ \dfrac{t_0}{\sqrt{\pi}\tau_l}\exp\left[-\left(\dfrac{t_0\tilde{\theta}}{2\tau_l}-\dfrac{A\tau_l}{t_0}\right)^2\right]\end{array}\right\}+\\ \exp\left[\left(\dfrac{A\tau_l}{t_0}\right)^2+A\tilde{\theta}\right]\left\{\begin{array}{l}A\left[erf\left(\dfrac{t_0}{2\tau_l}+\dfrac{A\tau_l}{t_0}\right)-erf\left(\dfrac{t_0\tilde{\theta}}{2\tau_l}+\dfrac{A\tau_l}{t_0}\right)\right]-\\ \dfrac{t_0}{\sqrt{\pi}\tau_l}\exp\left[-\left(\dfrac{t_0\tilde{\theta}}{2\tau_l}+\dfrac{A\tau_l}{t_0}\right)^2\right]\end{array}\right\}\end{array}\right\} & -1<\tilde{\theta}<1\\ -\dfrac{\sqrt{\pi}\beta I_0A^3}{2\alpha^2c_0C_Pt_0{}^2}\left[erf\left(\dfrac{t_0}{2\tau_l}-\dfrac{A\tau_l}{t_0}\right)+erf\left(\dfrac{t_0}{2\tau_l}+\dfrac{A\tau_l}{t_0}\right)\right]\exp\left[\left(\dfrac{A\tau_l}{t_0}\right)^2-A\tilde{\theta}\right] & \tilde{\theta}>1\end{cases} \quad （4）$$

Where I_0 is peak power density of pulse laser; $\tilde{\theta}=\tau_R{}^{-1}\left(t-z/c_0\right)$,z is transmission distance, τ_R is time of laser power before achieving peak power, c_0 is acoustic velocity in liquid; $A=\alpha c_0\tau_L$, α is optical absorption coefficient of liquid , τ_L and t_0 are pulse width and duration time of pulse laser respectively.

Optical-acoustic conversion efficiency is defined as the ratio of energy of acoustic pulses E_{ac} to energy of pulse laser projected into liquid E_L [4]. Through theoretical derivation, the conversion efficiency can be given by:

$$\eta=\frac{t_0}{2\rho_0c_0\varepsilon_L}\int_{-\infty}^{+\infty}\left[P\left(\tilde{\theta}\right)\right]^2d\tilde{\theta} \quad (5)$$

So, when the time-domain power distributions of pulse laser are sinusoid, triangle or Gaussian function waveform respectively, there optical-acoustic conversion efficiencies during the process of laser generation of acoustic waves can be given by the following equations:

$$\eta_S=\frac{\pi^3\beta^2I_0A^6}{4\alpha^4\rho_0c_0{}^3C_P{}^2\tau_L{}^2t_0{}^2\left(A^2+\dfrac{\pi^2}{4}\right)^2}\left[\frac{1+e^{-2A}-2Ae^{-2A}}{2A}+1-\frac{8A\left(1+e^{-2A}\right)}{4A^2+\pi^2}\right] \quad (6)$$

$$\eta_T=\frac{\beta^2I_0A^2}{\alpha^4\rho_0c_0{}^3C_P{}^2\tau_L{}^2t_0{}^2}\left[\left(-\frac{18}{A}+8\right)+\left(\frac{24}{A}+8\right)e^{-A}-\left(\frac{6}{A}+4\right)e^{-2A}\right] \quad (7)$$

$$\eta_G=\frac{\beta^2I_0A^3(3e^{4A}-16A^3e^{2A}-3-12A)}{6\sqrt{\pi}\alpha^4\rho_0c_0{}^3C_P{}^2\tau_L{}^3t_0erf(\dfrac{t_0}{2\tau_l})}\exp\left[2(\frac{A\tau_l}{t_0})^2-2A\right] \quad (8)$$

III. RESULTS AND DISCUSSIONS

In the simulation, water at room temperature is adopted as acting medium. Under the assumption that the peak power density is $I_0=1\times10^4W/cm^2$, the pulse width is $20\mu s$,the optical absorption coefficient is $0.1/cm$, the influence of peak power density of puled laser on optical-acoustic conversion efficiency at three time-domain power distributions is shown in Fig.1.As shown in Fig.1, the larger the peak power density is, the larger the conversion efficiency will be. The growth rate of conversion efficiency of Gaussian pulse laser generation of acoustic waves is the largest, in the next place is sinusoid pulse laser, and finally is triangle pulse laser.

Fig.2 and Fig.3 show the influence of optical absorption coefficient and pulse width of puled laser on the optical-acoustic conversion respectively. When the power distributions of pulse laser are sinusoid, triangle or Gaussian function waveform respectively, the change trends of conversion efficiency with the variation of optical absorption coefficient and pulse width are similar. With their increase, there are certain values of absorption coefficient or pulse width to make the conversion efficiency reach the maximum value. Under the same conditions, comparing with triangle and Gaussian pulse, the optical-acoustic conversion efficiency is the largest when the power distribution of pulse laser is sinusoid function.

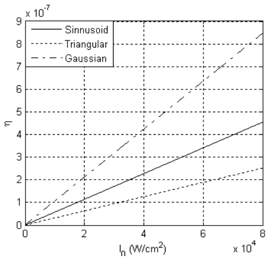

Fig.1. optical-acoustic conversion efficiency vs. peak power density of puled laser at three time-domain power distributions

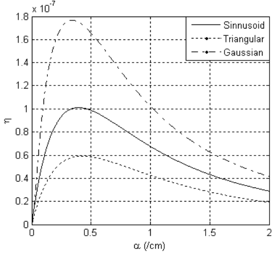

Fig.2. optical-acoustic Conversion efficiency vs. optical absorption coefficient at three time-domain power distributions

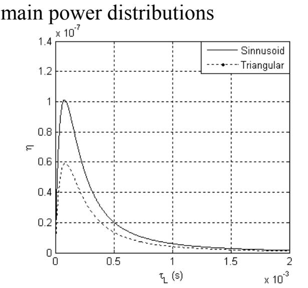

Fig.3. optical-acoustic conversion efficiency vs. pulse width at three time-domain power distributions

IV. CONCLUSION

Optical-acoustic conversion efficiency has been analyzed theoretically. The changes of conversion efficiency were simulated with the variation of the four factors, such as time-domain power distribution, peak power density and pulse width of laser, and optical absorption coefficient in fluid medium. The results can be used to choose optimum parameters of pulse laser used in fluid medium to implement laser generation of acoustic waves efficiently. The theoretical results are verified by our experiments. The research in this paper has great significance to the engineering application of photoacoustic source in the field of underwater communication.

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