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# ACOUSTIC GENERATION IN WATER BY PULSED LASERS

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## INTRODUCTION

There are a variety of mechanisms whereby a laser can be used to generate acoustic pulses in liquids, the most important of these being dielectric breakdown, vaporization and thermal expansion in decreasing order of incident optical power density. At low power densities, below the vaporization threshold, thermal expansion (known as thermoelastic generation) is the effect that dominates generation. At increased power densities, such that vaporization is induced, thermoelastic effects are still present, but generation via recoil forces from vaporizing liquid tends to be more efficient. At greatly increased power densities, dielectric breakdown dictates the source characteristics.

Breakdown is the most efficient generation mechanism, but is a complicated phenomenon which does not occur at a single isolated point in other than pure liquids. Despite these difficulties, Carome et al [1] demonstrated that the radiated wave in water was dipolar in nature, following generation by a 30 ns pulse from a Q-switched ruby laser. The estimated peak pressure close to the generation point was $\sim 5 \times 10^4$ kPa.

Vaporization has been studied principally at the surface of liquids, typically using a pulsed $CO_2$ laser operating at 10.6 μm in the infra-red. At this wavelength, the laser radiation is absorbed rapidly in water, effectively limiting the acoustic source to within a small distance from the surface. Under such conditions, Sigrist and Kneubühl [2] demonstrated that the radiated pulse was monopolar; other authors [3], however, have shown that the initial shock front may be followed by high frequency oscillations. Such a source has been used for the bathymetric mapping of shallow waters of up to 20 m depth by Hickman and Edmonds [4]. Frequency components of $\leq$ 1 MHz were shown to be generated by such a technique, the aim being to develop an airborne system.

Thermoelastic generation by pulsed lasers may occur in a variety of geometries. Generation close to the water surface has been studied by Sigrist and Kneubühl [2] ($CO_2$ laser) and Carome et al [5] (ruby laser with dyes in the water). Dipolar acoustic pulses were both detected experimentally and predicted theoretically following thermoelastic generation. At other laser wavelengths, absorption of laser radiation may become less marked, and the acoustic source then becomes a cylinder with a characteristic length dependent upon the optical absorption coefficient $\alpha$. The diameter of the acoustic source may be changed by varying the laser beam width, effectively allowing some control over radiated pulse shapes. The source thus formed is a broadside radiator, and was first studied by Westervelt and Larson [6] and Muir et al [7] for externally-modulated C.W. lasers. It was found, however, that generation efficiencies were low at these low laser powers, and hence other workers [8] investigated the use of high power pulsed lasers. In this paper, measurements of radiated acoustic pulses following thermoelastic generation within a cylindrical source will be described, using a laser delivering pulses with a peak power of $\sim 10^6$ W.

THE CYLINDRICAL THERMOELASTIC SOURCE

The geometry under investigation was cylindrically symmetric, with the laser beam having a radius R and acoustic detection occuring at a distance r from the centre of the cylindrical source. The laser pulse, of duration $\tau_p$, was absorbed in the water with an absorption coefficient $\alpha$, assumed to be a constant. Under such conditions, a simple approach would predict that acoustic amplitudes should increase with a decrease in $\tau_p$. This is reasonable, as thermal gradients would be expected to increase. However, a more rigorous approach also involves the radius of the cylindrical source, in terms of an acoustic transit time across the source of $\tau_a = R/c$, where c is the acoustic velocity. Such an approach has been described by Heritier [9] and Lai and Young [10].

Provided the perpendicular distance (r) of any detector from the heated cylinder is less than the illuminated length $\ell$ of the liquid, the problem becomes two-dimensional. Assuming a laser pulse that is gaussian in both time and intensity distribution with radius, Lai and Young [10] obtained a solution for the radiated thermoelastic pressure pulse P(r,t) in terms of the velocity potential $\phi$, given by

$$P(r,t) = K_a \frac{d\phi}{dt} = KK_a \tau_e^{-3/2} \frac{d\phi_o(\xi)}{d\xi} \qquad (1)$$

The contributions in (1) may be understood as follows. $KK_a$ is a term which determines the magnitude of the radiated pulse with certain variables, and is given by

$$KK_a = \frac{\alpha\beta E}{2\pi\sqrt{2}\, C_p} \left(\frac{c}{r}\right)^{\frac{1}{2}} \qquad (2)$$

where $\beta$ is the volume expansivity and E the incident laser energy. $\tau_e$ is a time scale factor, involving the two time scales of importance, $\tau_p$ and $\tau_a$, and is given by

$$\tau_e = [\tau_p^2 + \tau_a^2]^{\frac{1}{2}} \qquad (3)$$

Finally, the $d\phi_o(\xi)/d(\xi)$ term determines the shape of the acoustic pulse, via the expression

$$\phi_o(\xi) = |\xi|^{\frac{1}{2}} \left[\frac{\sqrt{2}}{\pi} K_{\frac{1}{4}}(\xi^2/4) + 2\theta(\xi) I_{\frac{1}{4}}(\xi^2/4)\right] \exp(-\xi^2/4) \cdot \left(\frac{\pi}{8}\right)^{\frac{1}{2}} \qquad (4)$$

where $\xi$ is a dimensionless time, given by

$$\xi = (t - \frac{r}{c})/\tau_e = t'/\tau_e \qquad (5)$$

Note that $K_{\frac{1}{4}}$ and $I_{\frac{1}{4}}$ are Bessel functions of imaginary argument, and $\theta$ is a unit step function. t' is a retarded time, where t' = 0 represents a delay of r/c after the initial laser pulse, the time taken for acoustic propagation from the centre of the source to the receiver. The shape function $d\phi_o(\xi)/d\xi$ is plotted as a function of $\xi$ in Fig. 1. Note that the predicted waveform shape is dipolar.

The expression for P(r,t) above will change with various radial intensity profiles of the laser beam. However, it is a general result that for a single laser pulse excitation, the radiated acoustic wave is a compression followed by a rarefraction, with a temporal width dependent upon $\xi$. Thus, the time duration of the acoustic dipolar pulse will depend on both $\tau_p$ and $\tau_a$, through $\tau_e$. For $\tau_a \gg \tau_p$, the diameter of the laser beam will effectively control the temporal width of the radiated acoustic wave, whose magnitude will increase with E, $\alpha$ and $\beta$.

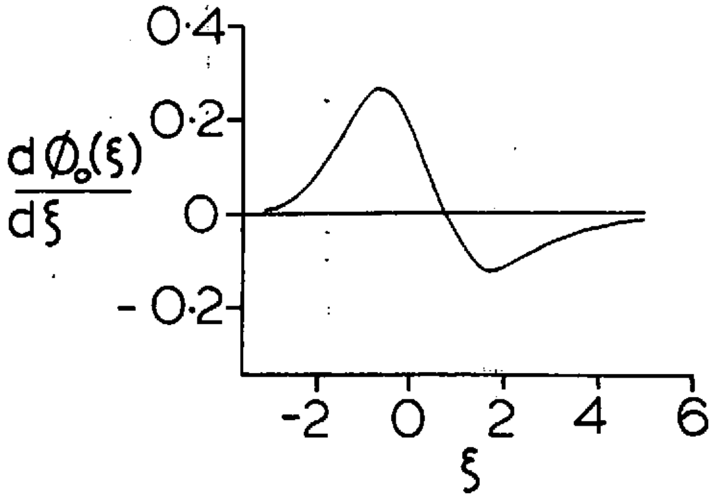


Fig. 1 The shape function $d\phi_o(\xi)/d\xi$, plotted as a function of the dimensionless time $\xi$.

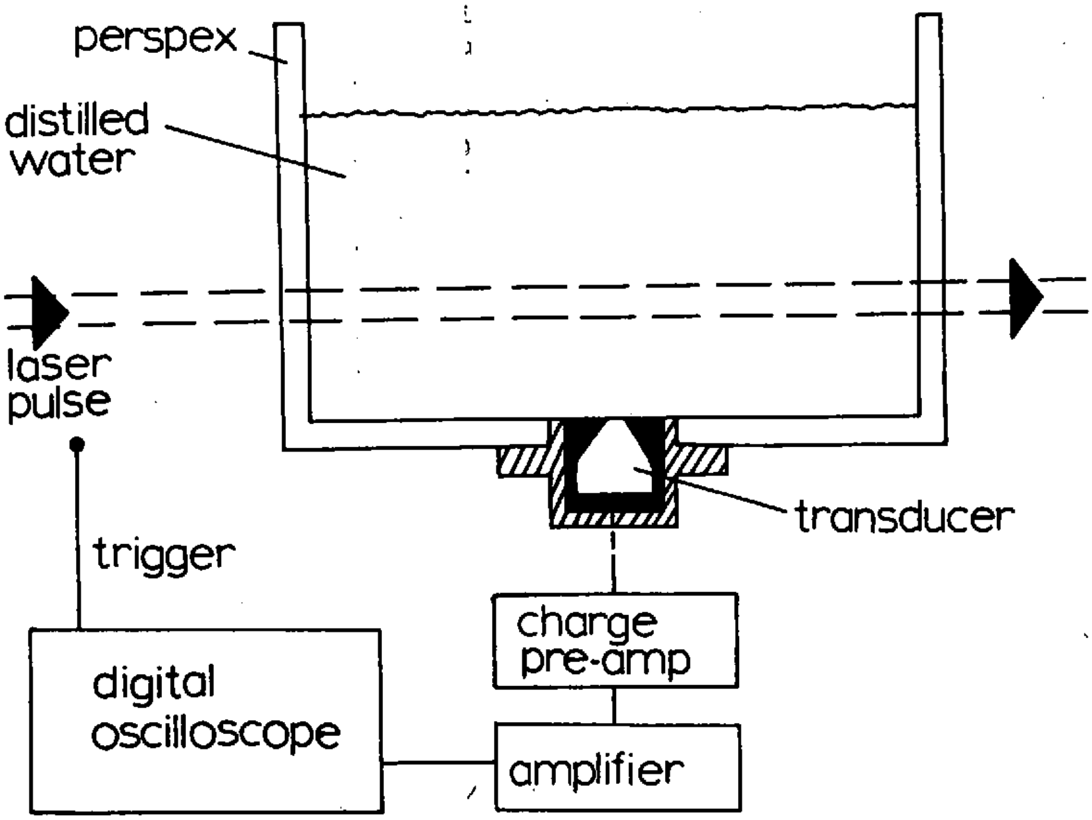


Fig. 2 Schematic diagram of apparatus.

EXPERIMENT AND RESULTS

The experimental arrangement used to study the cylindrical thermoelastic source is shown schematically in Fig. 2. Single laser pulses were supplied by a Q-switched frequency-doubled ruby laser, providing pulses of 30 ns duration in the UV at a wavelength of 347 nm, and with a typical energy of $\leq$ 200 mJ. The unmodified multimode beam was of ~0.5 $cm^2$ cross-sectional area, but in the experiments to be described was apertured with an iris diaphragm, to provide cylindrical beam diameters in the range 2-4 mm. Each laser pulse passed through the acrylic walls of a water tank containing distilled water, forming a cylindrical source by absorption of laser energy and subsequent thermal expansion. The path length through the water was 0.325 m, the absorption coefficient at 347 nm being found experimentally to be 0.66 $m^{-1}$. Note that the acrylic plastic chosen for the water tank walls was not unduly absorbent at 347 nm, allowing convenient passage of the laser pulse through the body of the water.

The acoustic pulses radiated cylindrically were detected by a thick (100 kHz) PZT transducer, machined with a conical section to discourage radial modes. It was designed so that the effective diameter of the sensitive area at its front face was 3 mm; hence the detector size was an approximation to a point receiver. Detected acoustic pulses were amplified by a charge amplifier and optional amplification stages, and captured on a digital oscilloscope with a 10 MHz sampling rate. Triggering was provided by the laser Q-switch signal. The waveforms were subsequently transferred to a Digital MINC 11/23 computer for storage, analysis and plotting.

As outlined in the previous section, the time duration of the radiated acoustic pulse from the cylindrical thermoelastic source would be expected to vary with laser beam diameter. These diameters were chosen such that the PZT transducer did not distort received waveforms unduly i.e. the separation in μs between the maximum and minimum of each dipolar pulse was $\leq$ the transit time for elastic waves from the front to back face of the PZT block (~5μs).

Fig. 3 shows a single detected acoustic arrival, following thermoelastic generation by a 2 mm diameter laser beam, with the distance between the centre of the laser beam and the detector (r) being 9 mm. The pulse was obviously dipolar, the estimated peak to peak pulse duration being 2.6 μs. Other examples of dipolar acoustic pulses, radiated following generation by larger laser beam diameters, are presented in Fig. 4 for r = 32 mm. As the diameter of the beam increased from 2.5 mm to 4 mm, Figs. 4(a)-(c), an increase in the dipolar acoustic pulse duration was also observed (as estimated by the time separation of each maximum and minimum). Note that the laser energy incident upon the water tank decreased with smaller beam diameters; the incident energy for each waveform is quoted in the captions to Figs. 3 and 4.

DISCUSSION

It is evident from Figs. 3 and 4 that dipolar acoustic pulses may be generated by pulsed lasers, following thermoelastic generation in a cylindrical symmetry in water. Further, the acoustic pulse duration was seen to increase with the diameter of the laser beam. Such results agree with predictions of theory [9,10], and results of previous experimental studies that used much smaller diameter focussed laser beams and optical detection [8].

Inspection of the shape of each dipolar acoustic pulse in Figs. 3 and 4 indicates that the initial compression was of smaller amplitude than the subsequent rarefraction in each acoustic arrival. This was a general result, and indeed was seen in other experimental investigations [8]. However, inspection of the shape function $d\phi(\xi)/d\xi$ (Fig. 1) indicates that theoretically the compression is expected to be the larger, following generation by a gaussian laser beam.

This disparity may be due to the fact that a multimode beam, and not a gaussian laser beam, was used in this work. Lai and Young [10] have predicted theoretically that marked changes in waveform shape might be expected for radial laser beam intensity profiles that are other than gaussian. As an example, consider two extreme cases, the gaussian and rectangular radial profiles. Assuming that contribution from electrostrictive mechanisms are negligible, the maximum signals from compression and rarefraction are respectively

$$P = \begin{cases} 0.54 \\ -0.25 \end{cases} KK_a \tau_e^{-3/2} \quad \text{at } t = \begin{cases} -0.6\tau_e \\ 1.75\tau_e \end{cases} \tag{6}$$

for a gaussian beam. The first compression peak for the rectangular beam is predicted to be

$$P = 0.51\ KK_A \tau_p^{-\frac{1}{2}} \tau_a^{-1} \quad \text{at } t = -\tau_a + 0.75\tau_p. \tag{7}$$

The two cases thus differ, and in general the amplitude of the rarefraction increases with respect to that of the compression for rectangular beams, provided $\tau_a >> \tau_p$, as is the case here. The multimode laser beam radial intensity profile was not measured, but was expected to be closer to a rectangular than a gaussian profile, especially following propagation through an aperture. However, a rigorous comparison would require knowledge of the laser beam profile, and this is planned as a future experiment.

It is instructive to estimate the peak pressures expected at the receiver, following thermoelastic generation in a cylindrical geometry. At 347 nm, with the absorption coefficient $\alpha = 0.66\ m^{-1}$, and using accepted values for the thermal properties of water, equation (6) would predict a compression peak of 275 kPa and a peak rarefraction of 127 kPa for the conditions of Fig. 3. The use of equation (7), assuming a rectangular profile, leads to an estimated peak compression of $1.2 \times 10^3$ kPa. It should be noted that for the case quoted, r = 9 mm; however, the peak pressures will decrease as $r^{-\frac{1}{2}}$, and as an example the compression peak would be ~37 kPa at 10 m for a rectangular profile. Also, as $\tau_a = R/c$, and because (1) contains a $\tau_e^{-3/2}$ term, the acoustic amplitudes will decrease with wider laser beams as an $R^{-3/2}$ dependence. The pressure amplitudes quoted above are only estimates, and have not been compared to experimental values; we plan to undertake this as future work.

## CONCLUSIONS

Acoustic generation in water by pulsed lasers has been demonstrated, using thermoelastic mechanisms in a cylindrical geometry. The dipolar nature of the radiated acoustic wave has been demonstrated, the time duration of which was dependent upon the laser beam diameter. This work may be considered a trial experiment to confirm general predictions; further work is now required to enable application of the technique to areas such as sonar.

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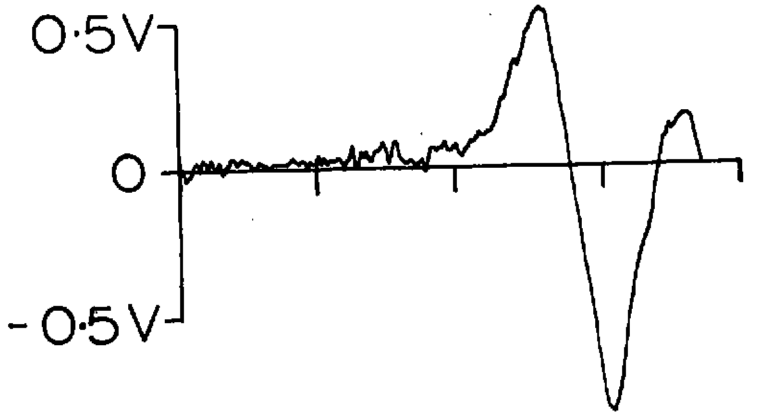


Fig. 3 The received acoustic pulse following thermoelastic generation by a 2 mm diameter laser beam. Incident laser energy was 12 mJ; r = 9 mm Horizontal scale 5 μs/div.

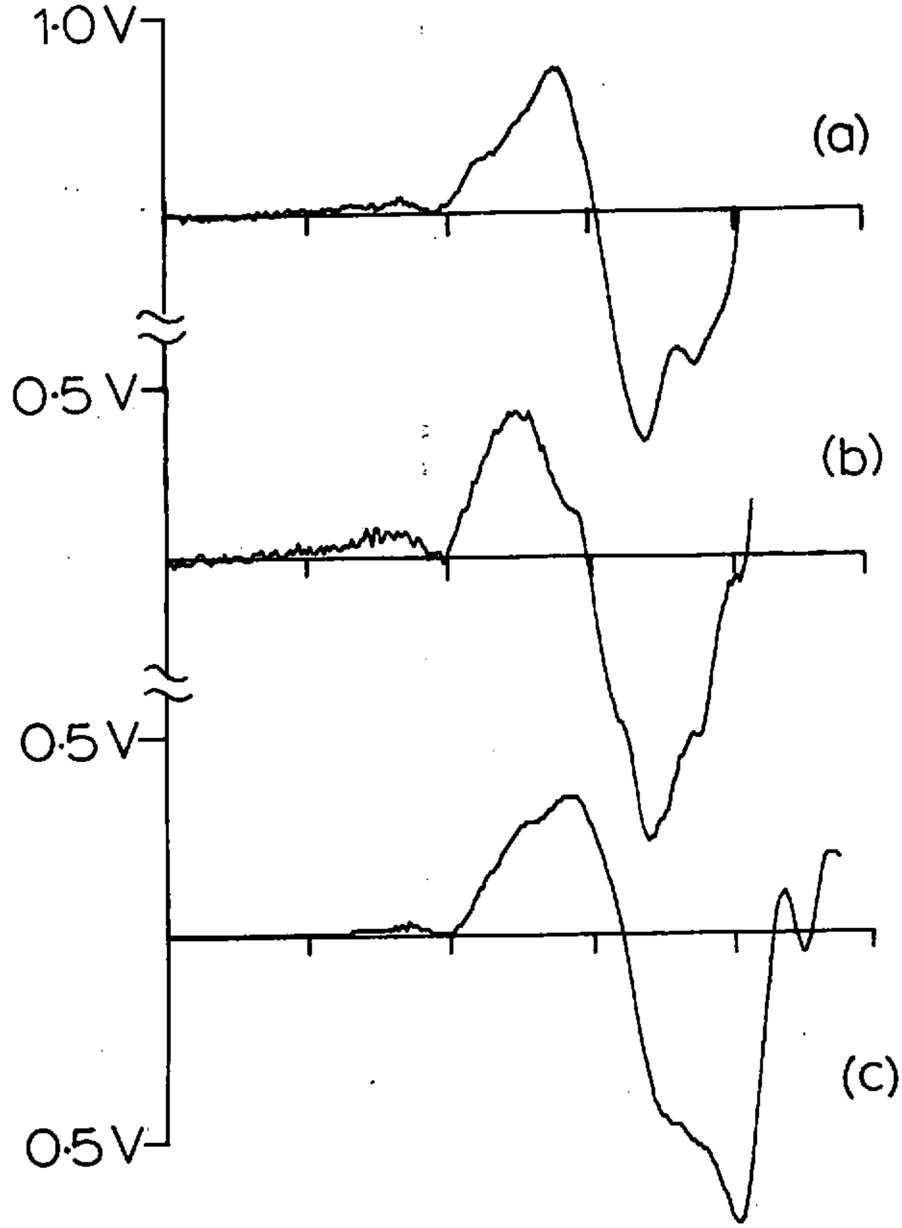


Fig. 4 Received acoustic pulses following generation by various diameters of laser beam, with r=32 mm.
(a) 2.5mm diameter, laser energy = 25 mJ;
(b) 3 mm diameter, laser energy = 37 mJ;
(c) 4 mm diameter, laser energy = 65 mJ.
Horizontal scale 5 μs/div. throughout.