# Study of laser-induced plasma shock waves by the probe beam deflection technique

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Laser probe beam deflection technique is used for the analysis of laser-induced plasma shock waves in air and distilled water. The temporal and spatial variations of the parameters on shock fronts are studied as functions of focal lens position and laser energy. The influences of the characteristics of media are investigated on the well-designed experimental setup. It is found that the shock wave in distilled water attenuates to an acoustic wave faster than in air under the same laser energy. Good agreement is obtained between our experimental results and those attained with other techniques. This technique is versatile, economic, and simple to implement, being a promising diagnostic tool for pulsed laser processing.

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Shock waves feature a strong dissipation of energy during propagation. The dissipated energy changes the state of the matter behind the shock front, and is thus related to the shock processing technique which employs high-power laser. The time-resolved study of the shock wave propagation occurring when a powerful laser beam is brought to focus has been extensively investigated theoretically and experimentally for gases[1−3], liquids[4−6], and solids[7−10]. In particular, the probe beam deflection technique has been shown to be a convenient, effective, and reliable diagnostic tool.

In this letter, a simple and effective detection technique based on fiber-coupling optical beam deflection principle is presented to probe the laser-induced shock wave in air and distilled water. Compared with other methods, this system is much more compact, sensitive, and easier to adjust. The recorded refraction of the probe beam enables us to determine the shock wave velocity and the pressure of the shock front. The influences of the characteristics of media are investigated on the well-designed experimental setup. Experimental results show that the shock waves in water have a smaller initial Mach number and decay faster than those in air under the same laser parameters.

In this method, we adopt a He-Ne laser beam to intersect the propagating shock wave. The probe laser is deflected in the direction of density gradient so that a corresponding transient angular deflection will create a signal in a position-sensitive detector[1]. A schematic diagram of the experimental arrangement is shown in Fig. 1. The shock waves are produced by focusing an expanded and collimated $Q$-switched Nd:YAG laser beam (wavelength of 1.06 $\mu$m, pulse width of 30 ns) perpendicular to the flat face of target in air and distilled water. The target, which is made of aluminum, is located inside a chamber with plane parallel quartz windows. The energy of the laser pulse is varied using a high-power attenuator and is measured before the focusing lens by an energy meter.

The probe beam is a He-Ne laser (wavelength of 623.8 nm, output power of 5 mW) with a diameter of 630 $\mu$m, focused by an aspherical lens ($f_1 = 30$ mm) to eliminate the spherical aberration. In order to detect the transient impact, the probe beam is focused parallel to the bare polished flat face of the target. The transmitted beam is focused by a microscope objective ($f_2 = 4$ mm) into a single-mode optical fiber that is mounted on a five-dimensional fiber-regulating-stand with 0.1-$\mu$m resolution. The output beam from the fiber is detected by a photomultiplier (Hamamatsu5773 with 2-ns rise time) and the signal is displayed on a digital oscilloscope (Tektronix 730A, 1 Gs/s) triggered with an external pulse for the power supply of the Nd:YAG laser. A narrow-band filter is used before the transmitted beam is coupled into the fiber to avoid the detection of scattered 1.06-$\mu$m laser light and plasma emission.

In order to adjust the distance of laser focus to the probe beam, we design a console with the minimum movement distance of 10 $\mu$m. It can control synchronously the movement of He-Ne laser, aspherical lens, microscope objective, interference filter, five-axis fiber-regulating-stand, and single-mode optical fiber in the direction perpendicular to the target surface.

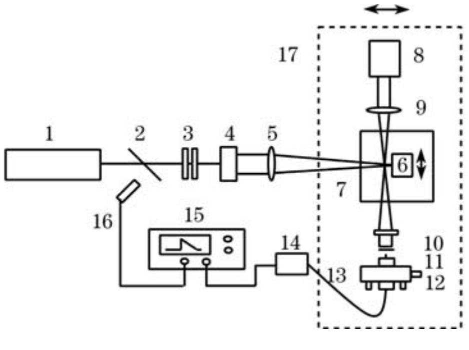

Fig. 1. Diagram of experimental setup. 1: $Q$-switched Nd:YAG laser; 2: beam splitter; 3: attenuator group; 4: concave lens; 5: convex lens; 6: target; 7: chamber; 8: He-Ne laser; 9: aspherical lens; 10: microscope objective; 11: interference filter; 12: five-axis fiber-regulating-stand; 13: single-mode optical fiber; 14: photomutiplier; 15: digital oscilloscope; 16: PIN photodiode; 17: console.

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Taking into consideration that the material surface could be out-of-flatness under the intense laser radiation, we parallel move the target to avoid the occurrence of the phenomenon and measure the average amplitude of ten pulses of the first peak of the deflection signal.

The propagating shock fronts in air and distilled water will cause the He-Ne laser beam to deflect at each intersection, giving rise to a corresponding pulse of the oscilloscope trace, as shown in Fig. 2. Under the condition of equivalent laser energy and propagation distances, shorter duration and lower intensity of the oscilloscope signal in liquid is expected due to the much lower compressibility coefficient.

The distances $r$ traveled by the shock waves are plotted as a function of the delay time $t$, as shown in Fig. 3. From the slope of the $r(t)$ curve, the shock wave velocity $v_\mathrm{s}$ values are derived. We get the shock wave velocity distribution versus propagation distance, as shown in Fig. 4. It indicates that the plasma shock waves decay approximately exponentially to sound waves after the end of the laser pulses. Figure 5 shows the Mach number $M$ of the shock waves as a function of the propagation distance. Compared with the shock waves in air, shock waves which transmit in water have smaller initial Mach number $M$ and decay faster, when they have been induced by laser pulses with the same energy. It is reasonable since the ratio of the wave impedance of water and air is $\sim 3.5 \times 10^6 : 1$[11].

From the $v_\mathrm{s}$ values, the shock pressure $p_\mathrm{s}$ in air is calculated by using the relationship[12]

$$p_\mathrm{s} = \frac{p_0}{\gamma + 1}[2\gamma\frac{v_s^2}{c^2} - \gamma + 1], \tag{1}$$

where $p_0$ denotes the static pressure, $\gamma$ is the adiabatic coefficient of the gas (in air, $\gamma = 1.40$), and $c$ is the normal sound velocity in air. The pressure in water is calculated by[5]

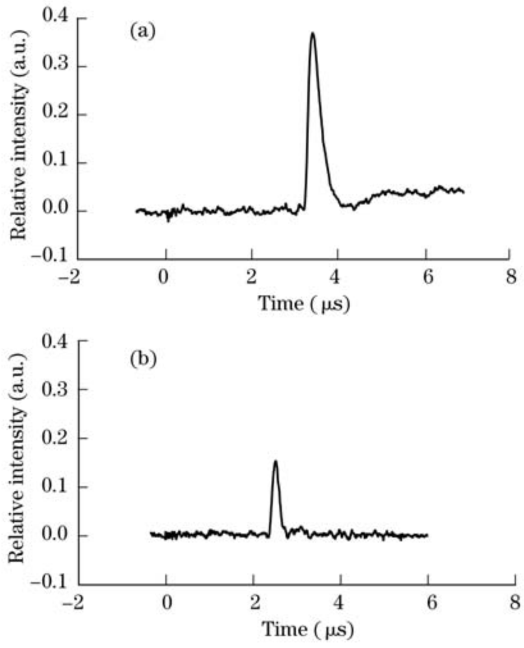

Fig. 2. Typical signals in different media of (a) air and (b) distilled water.

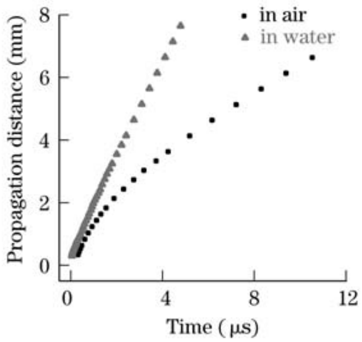

Fig. 3. Propagation of the shock front as a function of time under the laser energy of 185 mJ.

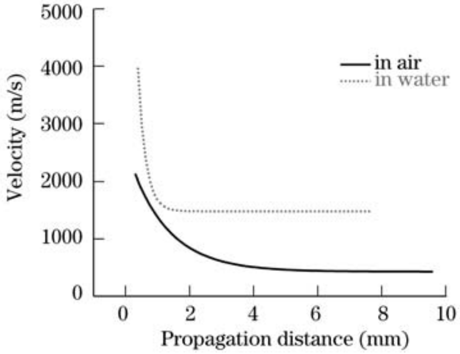

Fig. 4. Shock wave velocity versus propagation distance under the laser energy of 185 mJ.

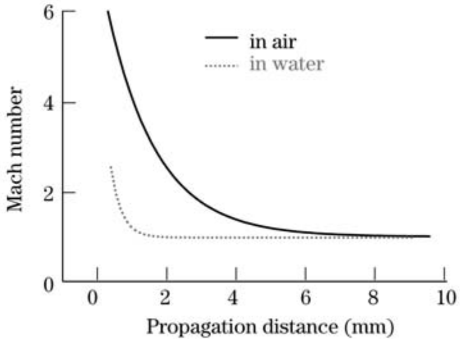

Fig. 5. Mach number of shock wave versus propagation distance under the laser energy of 185 mJ.

$$p_\mathrm{s} = c_1\rho_0 v_\mathrm{s}(10^{(v_s - c_0)/c_2} - 1) + p_0, \tag{2}$$

where $\rho_0$ denotes the density of water before compression by the shock wave, $p_0$ denotes the static pressure in water, $c_0$ is the normal sound velocity in water, and $c_1 = 5190$ m/s, $c_2 = 25306$ m/s. These relationships are based on the conservation of momentum at a shock front and on the Hugoniot curve data. Using the above relationships, the pressures at the shock fronts at $M = 2$ are given to be 4.56 atm in air and $2.25 \times 10^4$ atm in water, respectively. Since the pressure of shock front is determined by the physical characteristics of media, such as the density, acting forces of the molecules, and compressibility coefficient, the results are acceptable.

In conclusion, the laser-induced plasma shock waves propagating in air and water are systemically investigated in experiment. The results reveal that shock waves in water have a smaller initial Mach number and decay faster than those in air under the same laser parameters. This wide-band sensitive optical fiber sensor based on fiber-coupling optical beam deflection technique offers new possibility for the nondestructive examination of shock waves in gases and liquids. These research results will provide the theoretical and experimental reference for laser processing, laser medicine, and other corresponding fields.

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