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Optical probing of laser-induced shock waves in air

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Abstract. Shock Waves (SW) were produced in air by focusing the (0.25 J, 6 ns) second-harmonic ($\lambda = 532$ nm) Nd : YAG laser light into a stainless-steel cylindrical cell at a pressure from 200 to 760 Torr. The laser fluence at the focal point is > 5 GW/cm^2. The spatial variation and consequently the time evolution of the radial propagation velocity U of the generated shock waves were measured via a simple optical system utilizing a HeNe laser beam triply intersecting the propagating shock wave at three successive positions. Using a reflector, we were able to probe the traveling SW in six consecutive positions during its round trip. Good agreement was obtained between the experimental results and the predictions of the point strong explosion theory. It is shown that this method is simple with a fairly good precision. It therefore appears to be useful for the determination of the SW dynamic parameters, namely its Mach number, the pressure at the SW front, the thickness of the compressed air layer and the energy consumed in producing this layer.

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The striking phenomenon of plasma production and the subsequent shock-wave propagation which occurs 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 [1, 7] during the last three decades. Study of the behavior and the dynamic properties of the produced shock waves in gases on one hand represents a fundamental physical interest as a step in the understanding of various complex processes that occur in laser–gas interaction at intensity levels of the order 10^8–10^{13} W/cm^2, while on the other hand it is of special technological importance in the realization of controlled thermonuclear fusion. During the last decade a great deal of interest has been devoted to such experimental and theoretical studies of shock waves not only because of its demonstrated adoption in the research fields of inertial confinement fusion but also for many other applications in physics, chemistry, engineering, biology and medicine [8, 9].

Interferometric holography, shadowgraphy and Schlieren photography are the conventional experimental methods exploited for the spatial and temporal diagnosis of the propagating shock waves [10, 11]. Though good results have been attained with such techniques, they imply, however, a great deal of technical difficulties, besides the high cost of the required optical components. In this work we present a simple and accurate optical method to probe laser-induced shock waves in air. In this method we are adopting a HeNe laser beam to intersect the propagating SW at three successive positions. The recorded triple refraction of the HeNe beam enabled us to determine the shock-wave velocity, the pressure at the SW front, the thickness of the compressed air layer and the energy consumed in producing this layer. Experimental results obtained are in good agreement with the predictions of the point strong explosion theory. Beside gases this method is also applicable for similar measurements in transparent liquids.

1 Experimental procedure

The experimental layout is shown in Fig. 1. The second harmonic of a Nd:YAG Q-switched laser (Surelite I - Continuum) is used to obtain shock waves following the breakdown in the air. Typical outputs at wavelength of 532 nm were 250 mJ in about 6 ns FWHM pulses at 10 Hz repetition rate. Laser light is focused by a quartz aspheric lens L_1 of focal length 15 cm inside the cylindrical stainless steel cell C. The measurements were performed in air at ambient pressures of 200, 350, and 760 Torr. The transmitted Nd-laser beam is monitored via a photodiode (not shown in Fig. 1) to evaluate the absorbed energy E during the plasma formation growth. At the same time the corresponding incident energy of the Nd-laser is measured using a calibrated calorimeter.

Using two corner cubes, a HeNe laser beam is used to probe the propagating SW front at three consecutive positions as shown in Fig. 1. A schematic view of the exploding shock wave front path through the probing beams is shown in Fig. 2. A removable glass reflector R is

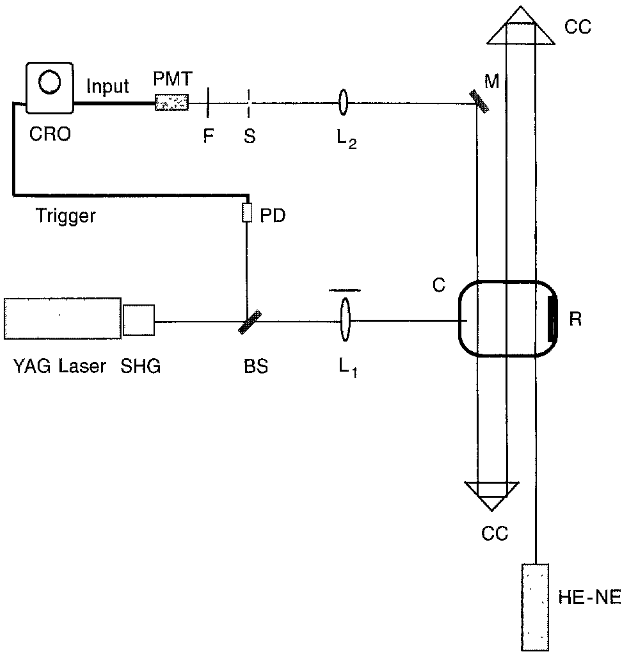

Fig. 1. The experimental arrangements. *SHG* = second harmonic generator, *BS* = beam splitter, *PD* = Photo diode, L_1, L_2 = focusing lenses, *C* = vacuum chamber, *R* = reflector, *CC* = corner cube, *M* = mirror, *S* = slit, *F* = interference filter and *PMT* = photomultiplier tube

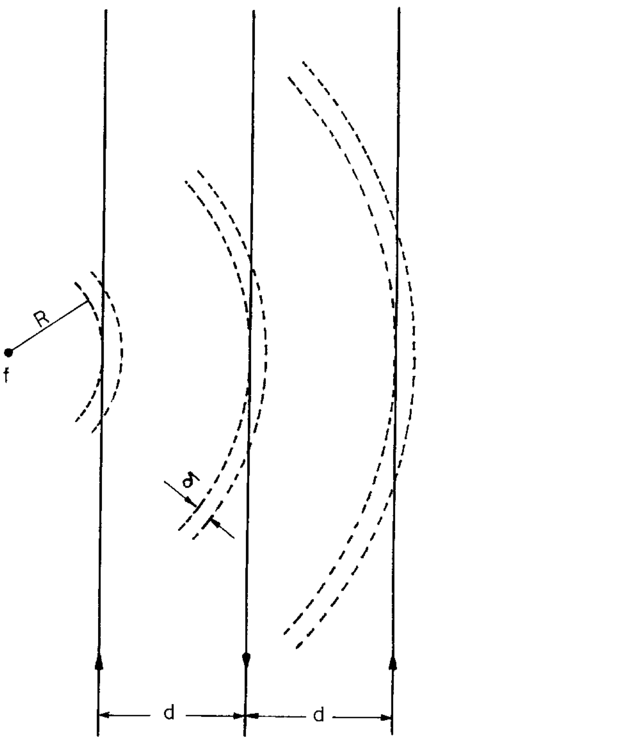

Fig. 2. Schematic view of the propagation of the shock-wave front showing the geometrical path of the three HeNe beams. (d = 10 mm)

used to reflect the shock wave back (imploding), resulting in the deflection of the HeNe laser beam three other times. The HeNe beam is focused by a lens L_2 on a narrow slit S then it passes through an interference filter F to avoid scattered light in front of the photomultiplier tube (PMT) which is connected to the storage oscilloscope. The CRO-signal consists of three or six negative pulses depending on whether the reflector R is removed or not. Figure 3a, b shows typically detected signal in both cases.

2 Results and discussion

The propagating shock front will cause the HeNe laser beam to deflect (refract) at each intersection giving rise to a corresponding negative pulse of the oscilloscope trace (see Fig. 3a and b). Since the two HeNe beams are 10 mm apart and as the time intervals between the corresponding oscilloscope signals are known, we can determine the velocities U_1 and U_2 of the propagating shock at two successive time intervals. The radius R of the shock wave is varied by moving the focusing lens L_1 towards or away from the first HeNe beam to study the dependence of U on R. According to the self-similar solution of the point strong explosion theory, the time evolution of the radius R and the Mach number M of the produced shock waves are given by [12]:

$$R = (E/\alpha\rho_0)^{1/5} t^{2/5}, \tag{1}$$

$$t = (2/5v)^{5/3} (E/\alpha\rho_0)^{1/3} M^{-5/3}, \tag{2}$$

where E, v and ρ_0 are the absorbed energy, sound speed at room temperature and the unperturbed gas density respectively, α is a gas-dependent constant ranging in 0.5–0.8.

Since in our case the absorbed energy is relatively low ($E < 0.25$ J), so we have to take into consideration the counter-pressure of the shock wave [11]. The motion of the propagating SW in this case is no longer self-similar after few nano seconds from the initial breakdown. The non-self-similar formulation of the time evolution of the Mach number is given by the following expressions:

$$t = (2/5v)^{5/3} (E/\alpha\rho_0)^{1/3} M^{-5/3} (1 + \beta M^{-2}), \tag{3}$$

where

$$\beta = w(\nu + 1)(\nu + 2)/\nu(2 + 3\nu), \tag{4}$$

$$\rho/\rho_0 = (\gamma + 1)/(\gamma - 1 + 2M^{-2}). \tag{5}$$

In the above equations, w is a constant numerically determined (~ 2), ν represents the dimensionality of the system ($= 3$ for spherical symmetric shock waves), ρ/ρ_0 is the density jump in the compressed air layer and $\gamma = C_p/C_V$ is the adiabatic coefficient of the gas.

In Fig. 4 the Mach number M of the shock wave is given as a function of the shock front position R (SW radius) for three different values of the ambient pressure P_0, namely 200, 350, and 760 Torr. The time evolution of the Mach number is depicted in Fig. 5 for the same set of counter-pressures. A fairly good agreement is obtained between the experimental results and the point strong explosion theoretical calculations, taking into account the counter-pressure.

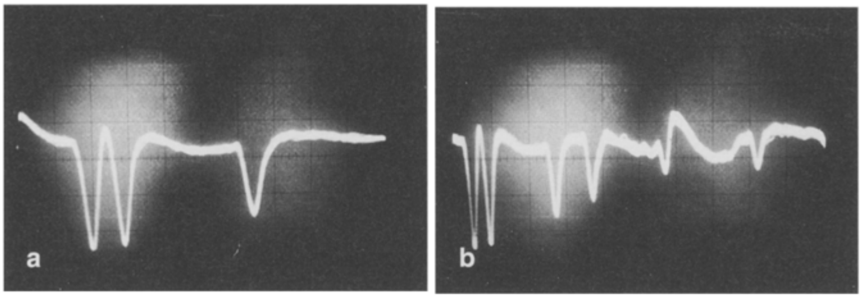

Fig. 3a, b. Typical Photomultiplier output at $P_0 = 350$ Torr (**a** without reflector, **b** with reflector). The time scale is 5 μs/div (**a**) and 10 μs/div (**b**). The focal point is 3 mm from the first HeNe beam

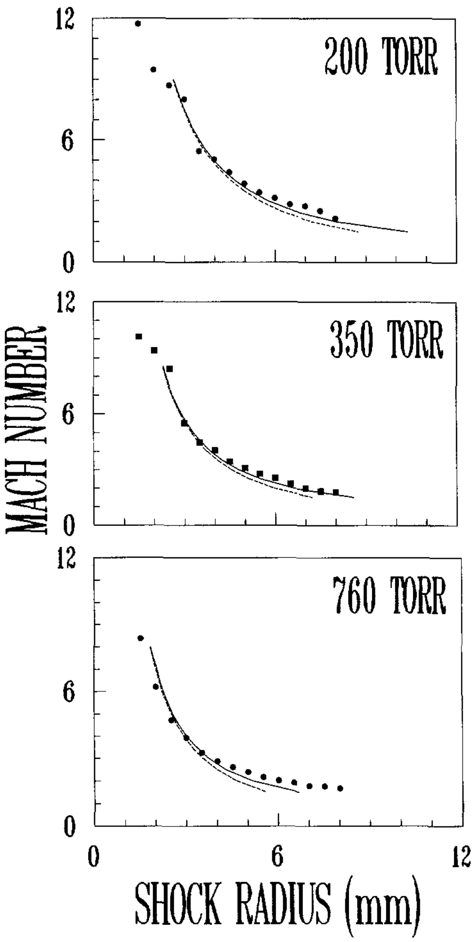

Fig. 4. Shock-wave Mach number vs shock radius. The points are the experimental data, dashed curve is the theoretical calculation of the point strong explosion model and the solid curve is same calculations taking into account the counter-pressure a head of the SW

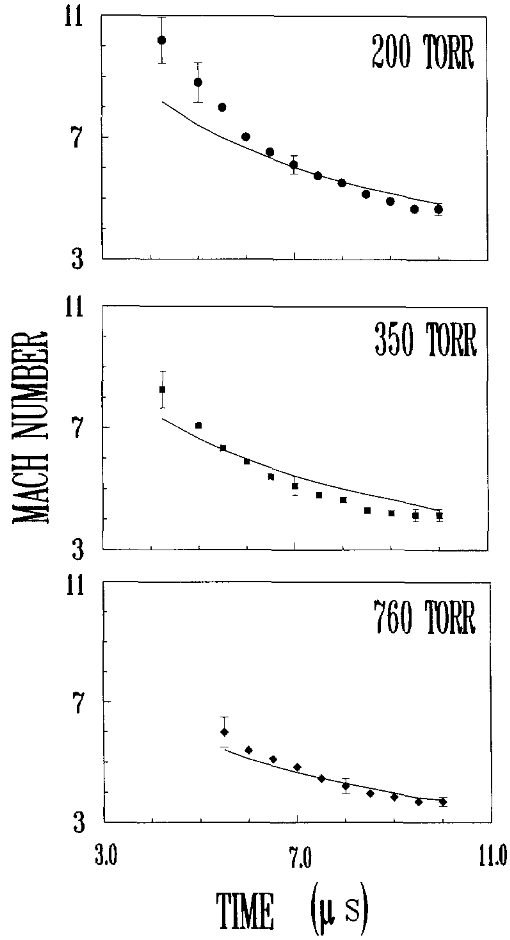

Fig. 5. The time evolution of the shock-wave Mach number. The points are the experimental data while the curves have been calculated from (3)

To evaluate the pressure P at the shock-wave front knowing its velocity U, the following formula is used [12]:

$$P = P_0 + (1 - \rho_0/\rho)\rho_0(U - v)^2, \tag{6}$$

where ρ_0/ρ is the reciprocal of the density discontinuity given by (5). Using (6), the pressure at the shock-wave front at $R = 2.5$ mm for ambient pressures 200, 350, and 760 Torr is given to be 14.6, 19.9, and 30 atmospheres, respectively.

The thickness δ of the compressed air layer (Fig. 2) can be determined from the work-energy theorem:

$$W = \Delta K, \tag{7}$$

where W is the work done in compressing this air layer and ΔK is the change in its kinetic energy. For spherical symmetrical shock of radius R, thickness δ, moving a distance d with initial velocity U_1 and final velocity U_2 we can write

$$P = (1/2d)\delta\rho_0(U_1^2 - U_2^2). \quad (8)$$

Hence,

$$\delta = 2Pd/\rho_0(U_1^2 - U_2^2), \quad (9)$$

where P is given by (6).

Using (9) for $R = 2.5$ mm, the compressed layer thickness δ is found to be 3.7 mm. Compared to the layer thickness in case of laser-driven shock waves in water ($\delta = 0.125$ μm) [6], this value looks reasonable since the ratio of the compressibility coefficients of air and water is $\sim 1:4 \times 10^{-5}$ [13] and the incident laser energy is higher in the water case. The time taken to form this layer is

$$t = \delta/U_1 \sim 1.4\ \mu\text{s}.$$

From (7) the work W done in compressing this air layer is found to be 0.07 J which means a conversion efficiency of light energy to mechanical compression of $\sim 28\%$ at 200 Torr ambient pressure.

In conclusion, the dynamics of laser-induced shock waves in air have been studied experimentally via an optical method which is much easier than the conventional methods used for this task. The experimental observations were compared with the point strong explosion theory predictions and good agreement is obtained when the counter-pressure is taken into consideration. This method can be exploited for similar experiments in all transparent fluids. In liquids, however, sharp oscilloscope signals are expected due to the very low compressibility coefficient in such cases.

References

1. J.F. Ready: *Effects of High-Power Laser Radiation* (Academic, New York 1971)
2. G.V. Ostrovskaya, A.N. Zaidel: Sov. Phys-Usp. **16**, 834 (1974)
3. C.G. Morgan: Prog. Phys. **38**, 621 (1957)
4. D.C. Emmony: Infrared Phys. **25**, 133 (1985)
5. S. Ridah: J. Appl. Phys. **64**, 152 (1988)
6. M.A. Harith, V. Palleschi, A. Salvetti, D.P. Singh, M. Vaselli, G.V. Dreiden, Yu.I. Ostrovsky, I.V. Semenova: J. Appl. Phys. **66**, 5194 (1989)
7. N. Bloembergen: IEEE J. QE-**10**, 375 (1974)
8. V.P. Zharov, V.S. Letokhov: *Laser Optoacoustic Spectroscopy*, Springer Ser. Opt. Sci., Vol. 37 (Springer, Berlin, Heidelberg 1986)
9. V. Palleschi, D.P. Singh, M. Vaselli, (eds.): *Proc. XX Int'l Conf. on Phenomena in Ionized Gases*, Barga, Italy (1991)
10. Yu.I. Ostrovsky, M. Butusov, G. Ostrovskaya: *Interferometry by Holography*, Springer Ser. Opt. Sci., Vol. 20 (Springer, Berlin, Heidelberg 1980)
11. M.A. Harith, V. Palleschi, A. Salvetti, D.P. Singh, G. Tropiano, M. Vaselli: Opt. Commun. **76**, (1989)
12. L. Sedov: *Similarity and Dimensional Methods in Mechanics* (MIR, Moscow 1982)
13. R.C. Weast: *Handbook of Chemistry and Physics*, 60th edn. (CRC, Boca Raton, FL 1979, 1980)