Cavitation and shock waves in water, stimulated by laser filament

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Abstract—Using shadow photography technique we have observed shock acoustic wave from optical breakdown, excited in water by tightly focused Cr:Forsterite femtosecond laser beam, and have found two different regimes of shock wave generation by varying only the energy of laser pulse. At low energies a single spherical shock wave and cavitation bubble is generated from laser beam waist, and shock wave radius tends to saturation with energy increasing. At higher energies long laser filament in water is fired, that leads to the cylindrical shock wave generation and cavitation bubble in every nonlinear focus. The diameter of cavitation bubble depends on the distance from the first nonlinear focus. From shadow pictures we also estimated maximal velocity in the shock wave front of 3200±150 m/s and pressure of 240±30 MPa.

Keywords—laser-induced shock waves and cavitation; laser-induced plasma; filamentation.

When femtosecond laser radiation with peak power, higher than critical power of self-focusing (Pcr), propagates in the transparent medium, extended filaments of optical radiation and accompanying plasma channels are formed [1]. The high density (10¹⁸–10¹⁹ cm⁻³) plasma is formed in the nonlinear focuses. In each focus plasma grows and in liquids it becomes the center of laser-induced spherical shock wave and cavitation bubble [2]. The diameter of cavitation bubbles formed in the nonlinear focuses decreases moving outward the laser beam. It is interesting, despite of rapid decrease of energy in each nonlinear focus, the array of spherical shock waves forms one cylindrical shock wave. For shock waves and cavitation observation shadow photography technique was used. In the experiments Cr:forsterite femtosecond laser (wavelength is 1240 nm, pulse duration about 140 fs, laser energy up to 150 µJ, repetition rate is 10 Hz) was employed as a pump pulse. The second harmonic of Cr:forsterite or ND:YAG lasers was used as a probe beam. The experiments were carried out with lens (N.A = 0.4, focusing distance in air 3 mm). Using this focusing regime we have observed the generation of shock wave, when filamentation process is developed. At low laser pulse energy only single spherical shock wave is generated (Fig. 1a), at higher laser pulse energy several dotted sources, isolated from each other, created complex envelope of shock wave (Fig. 1b,c). With the increase of laser energy the additional shock waves are generated from new plasma sources in the filament, forming a single cylindrical shock wave (Fig. 1).

Fig.1. The shadowgrams of shock acoustic waves (a)-(d), delayed on 18.6 ns and cavitation bubbles delayed on 2.3µs from optical breakdown at different incident laser pulse energy. Dashed line shows the center of initial plasma formation region. Arrow shows laser pulse direction. The dark regions in shadowgrams shows shock wave location and dark regions in the center of images shows cavitation region.

In the experiments we have found, that shock wave diameter tends to saturation as square root of incident pulse energy. It can be explained, using the fact, that energy transferred from laser radiation to plasma and then from plasma to each shock wave in the optical breakdown volume is limited, due to the number of electrons limitation in the volume, where laser-plasma interaction is taken place. The shock wave energy is square root to its radius, due to mass flow conservation and its spherical symmetry [2]. Using the experimental dependence of the diameter of shock wave on time it is easy to estimate the shock wave front velocity. To estimate the pressure at the shock front an empirical equation was used [2]. For incident laser energy of 130µJ shock wave front velocity is 3200±200 m/s. The shock pressure equals to 240±30 MPa.
