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Abstract

A Mach-Zehnder interferometer was used for analysis of pressure waves generated by ultrashort laser pulse ablation of water. It was found that the shock wave generated by plasma formation rapidly decays to an acoustic wave. Both experimental and theoretical studies demonstrated that the energy transfer to the mechanical shock was less than 1%.

Results and Discussion

Fig. 1 shows the schematic of the Mach-Zehnder interferometer. The Nitrogen-pumped dye laser was used as a probing light source. The green beam from the dye laser was split in a 50:50 beam splitter. One of the beams passes through a water-filled cuvette on which the ultrashort laser pulse (USLP) is incident and generates surface ablation. Another water cuvette was placed in the other beam path to match the path difference between the two beams. The pressure waves generated by the surface ablation caused the fringe shift, which can be correlated to the pressure. The fringe shift was recorded on a CCD camera with a resolution as high as 1 μm per pixel.

Fig. 2 shows the typical interferogram with fringe shift due to the spherical wave generated from the small surface area. Assuming axial symmetry and triangular pulse shape, the peak pressure can be calculated. The maximum fringe shift is

$$\Delta\varphi_{\max} = \frac{2\pi a}{b}$$

The peak change of refractive index is calculated using

$$n_{peak} = \frac{\lambda\Delta\varphi_{max}}{2\pi s} f(s/2R)$$

$$f(\alpha = s/2R) = \frac{\alpha^3}{\alpha + (1-\alpha)\ln\left(\sqrt{\frac{1-\alpha}{1+\alpha}}\right)} \approx 1.5\ (s << R)$$

using a triangle-like pulse shape function. The ablation threshold for water ablation is shown in Fig. 3. The threshold was defined as beam fluence (J/cm^2) that causes formation of the spherical waves. As expected the threshold increases with increasing pulse width and the slope of the threshold follows typical ablation threshold patterns for other dielectric ablation.

The estimated peak pressure was calculated for various pulse widths and at multiples of the threshold intensity; the results are presented in Fig. 4. The pressure is several kbars at 50 μm for most cases and rapidly decays to 200 – 300 bars after traveling 200 – 300 μm. The solid lines are the curve fit to the data. It seems that the peak pressure is inversely proportional to the travel distance, which is expected in normal acoustic waves.

Fig. 5 shows the radius of the spherical waves as a function of time. We used various pulse widths and beam intensities. It was found that the speed of the waves is dependent on the ratio of the intensity to the threshold but not on the pulse width. The speed of the pressure waves was approximately 1.53 km/sec for all cases. The typical speed of sound in water is 1.48 km/sec. It was also found that the waves initiated by more intense pulses were more advanced due to the fast initial propagation.

The total energy in the pressure waves was estimated using the following expression:

$$E = \int \frac{p(t)^2}{c_0 \rho_0} 2\pi R^2 \, dt = \frac{2\pi R^2 p_{peak}{}^2 \tau}{3 c_0 \rho_0}$$
$$= \frac{2\pi R^2 p_{peak}{}^2 \Delta x}{3 c_0{}^2 \rho_0}$$

The energy conversion rate for various pulse widths and beam intensities was calculated and presented in Fig. 6. An important observation in this study is that the conversion efficiency is less than 1% for all cases. This result was confirmed by a theoretical calculation. We used the one dimensional hydrodynamics code "HYADES" to calculate the conversion efficiency and this result also shows that the efficiency is less than 1% [1]. This result supports the small collateral mechanical damages induced by USLP as reported in many other publications [2-3].

Acknowledgments

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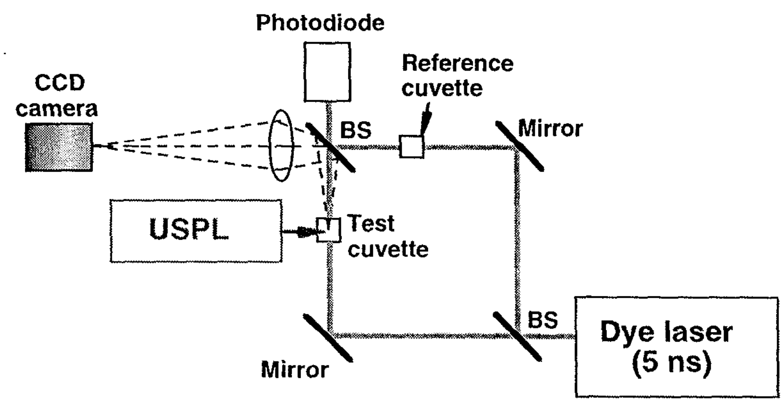

Fig. 1. Schematic of Mach-Zehnder interferometer

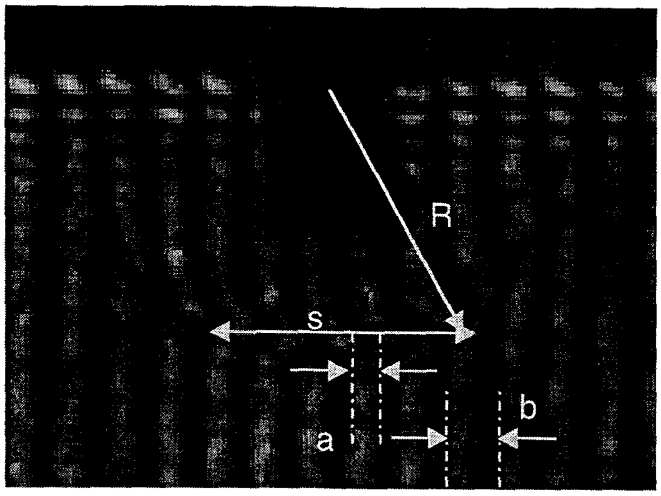

Fig. 2. Typical interferogram obtained using Mach-Zehnder interferometer. Spherical wave generates the symmetric fringe shift.

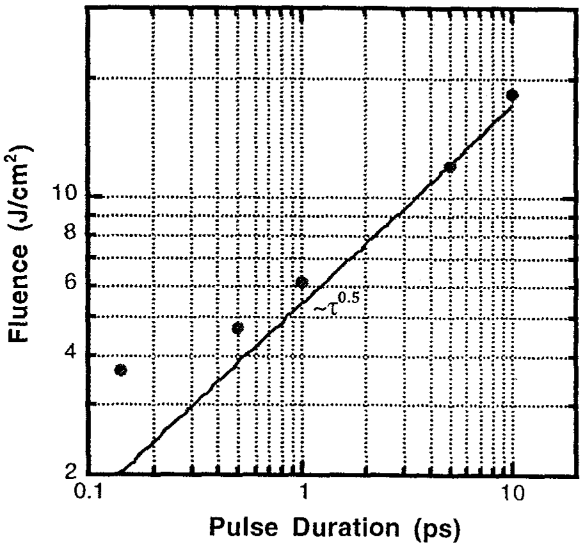

Fig. 3. Thresholds for spherical wave formation for various pulse durations.

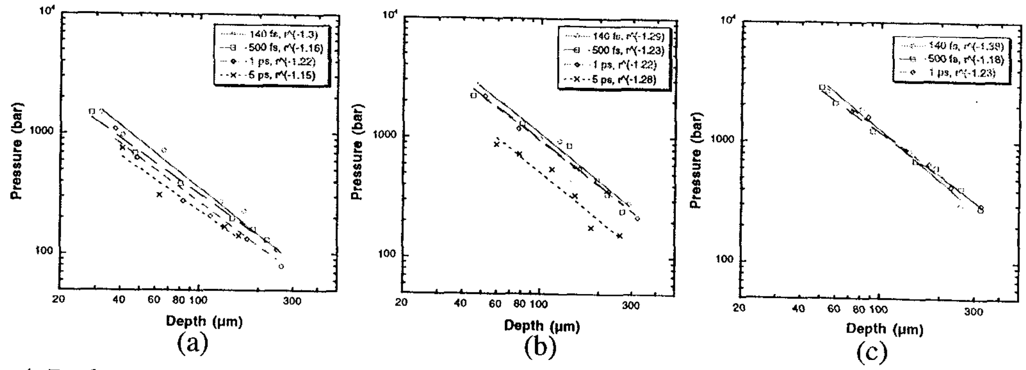

Fig. 4. Peak pressures calculated using the fringe shift of interferograms at (a) threshold, (b) 2 x threshold, and (c) 3 x threshold.

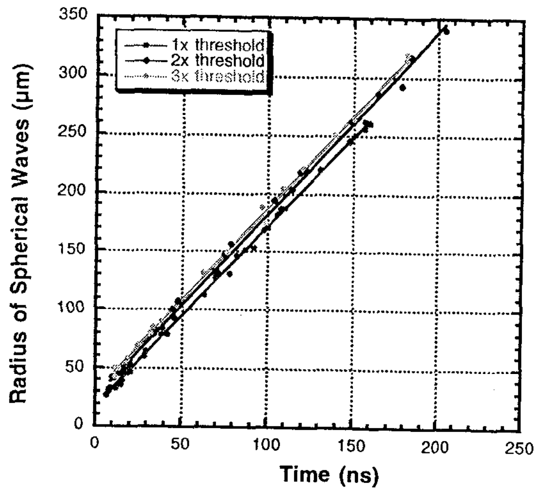

Fig. 5. Propagation of pressure wave front with time. Speed of waves are calculated using the curve-fit procedure.

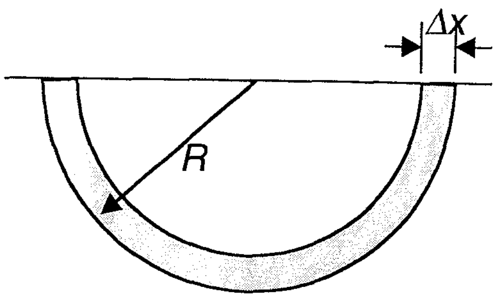

Fig. 6. Typical wave shape.

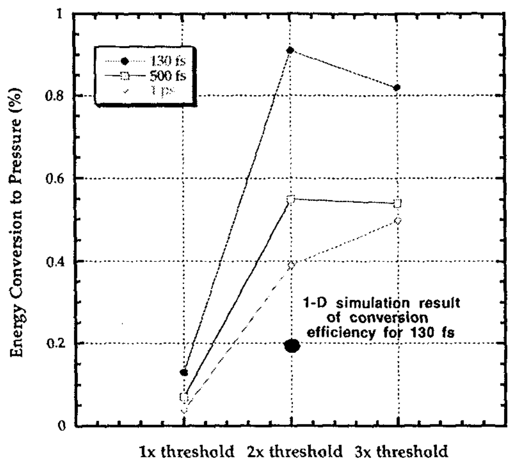

Fig. 7. Energy transfer to the pressure waves estimated at various pulse widths and beam intensities. Results of HYADES calculation is also shown.