Fragmentation process induced by microsecond laser pulses during lithotripsy

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A fiber optic stress sensing technique is applied to evaluate the fragmentation mechanism for pulsed dye-laser lithotripsy. We demonstrate for the first time that the fragmentation process with microsecond laser pulses originates from the shock wave induced by the cavitation bubble collapse. This shock occurs some hundreds of microseconds after the laser pulse. The shock induced by the plasma expansion, which occurs during laser irradiation, has a minor effect.

Laser-induced shock wave lithotripsy was first proposed by Fair[1] and Watson *et al.*[2] Since these early experiments, reports of lithotripsies with *Q*-switched Nd:YAG,[3] flashlamp-pumped dye,[4,5] and *Q*-switched alexandrite[6] lasers have been published. Nevertheless, until now the widest clinically used laser lithotriptor is the dye laser. The laser-induced shock waves were first observed by Bell and Landt[7] and Anderholm[8] in the late 1960's. In laser lithotripsy, the procedure consists of fragmenting the targets, urinary or biliary stones, by such laser-generated shock waves.[9,10] The laser pulse, delivered through an optical fiber, is absorbed by the stone; this very localized energy absorption results in the formation of a plasma which expands. Due to confinement in the surrounding liquid, the expanding plasma and vapor form a cavity, respectively a cavitation bubble. This bubble grows to a maximal size and then collapses on itself some hundreds of microseconds later.[11–14] Shock waves induced during plasma expansion and bubble collapse are at the origin of the mechanical stresses experienced by the target. Acoustic studies and microsecond-long flash photography of dye laser-induced stone fragmentation mechanisms have been previously made by Teng *et al.*[13,14] From these studies, Teng *et al.* concluded that fragmentation occurs in response to the shock waves generated during plasma expansion, bubble collapse being an unlikely major cause of stone damage. In this letter, we report on the mechanical stresses generated by the laser-induced pressure transients. These stresses are detected by monitoring the transmission losses of irradiated target fibers. Clear evidence that, for dye-laser lithotripsy, the most intense stress occurs in response to the cavitation bubble collapse is presented. As a consequence cavitation is not, as previously stated, a satellite phenomenon, but is the governing mechanism for dye laser-induced lithotripsy.

The experimental setup used to observe the fragmentation occurrences is shown in Fig. 1. A flashlamp-pumped Rhodamine 6G dye laser (developed at our center), delivering pulses of 2.5 μs at a wavelength of 596 nm has been used. The laser light is coupled into a 200-μm core diameter all-silica fiber with a 0.22 N.A. Pulses up to 180 mJ at repetition rates up to 10 Hz can be delivered at the fiber tip. The fiber tip is placed directly in contact with the target. Targets are model stones of white marble or all-silica optical fibers, with 50- and 125-μm core and cladding diameters, respectively. The fiber cladding is painted black in order to improve initial absorption. The target is placed in water, 50 mm below the surface in order to insure a complete confinement of the laser-induced plasma.[13] The laser-generated acoustic transients on model stones and fibers are detected with a PVDF needle-probe hydrophone (Müller) with a specified rise time of 80 ns placed approximately 6 mm away from the laser-target interaction zone. Due to the pressure decrease as a function of the distance,[15] the recorded pressure is substantially lower than that at the target and represents only a lower limit of the actual pressure experienced by the target. Mechanical stress measurements have been performed on optical fibers only. A 5-mW HeNe laser is coupled to the sensing target fiber. The transmitted signal is detected by a photodiode (Siemens, SFH 202a) with a 3-ns rise time. Acoustic transient and time-resolved transmission measurements are monitored synchronously with a 350-MHz oscilloscope (LeCroy, Type 9450).

Typical acoustic transients associated with the plasma occurrence on stones at a laser fluence of 318 J/cm^2 (100 mJ/pulse) are presented in Fig. 2. The pressures indicated in this figure have been evaluated from the measured PVDF needle probe values by taking into account the limited response time of the detector using the correction factor evaluated by Vogel and Lauterborn.[12] The horizontal scale indicates the delay with respect to the start of the laser pulse. Measured delays include the traveling time of the acoustic wave to the PVDF detector. The acoustic signature exhibits three pressure transients. The first transient, observed at a delay of 3.9 μs, is associated with plasma expansion. The second transient results from the first collapse of the cavitation bubble at a delay of 870 μs. This delay is related to the maximal size reached by the cavitation bubble.[16] A third transient induced at the second collapse of the cavitation bubble, after rebound, is observed at a delay of 1.3 ms.

Clearly, the strongest acoustic transient is induced by the collapse of the cavitation bubble. Indeed, the maximal pressure measured at the cavitation bubble first collapse is up to five times higher than during plasma expansion. Moreover, the width of the pressure transient is shorter at the bubble collapse (360-ns FWHM) than during the plasma expansion (2.5-μs FWHM). Interestingly, the third pressure transient induced by the second collapse of

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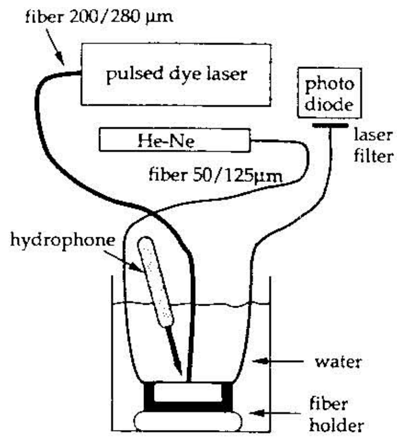

FIG. 1. Experimental setup for fiber stress measurement and fiber fragmentation experiments. Acoustic signal measurements on stones are measured with the same experimental arrangement.

the cavitation bubble after rebound still has the same amplitude as the plasma expansion transient.

The pressure and temperature transients created at the surface of a target fiber strongly alter its transmission. Figure 3 shows the light transmission of such a target fiber recorded simultaneously with the needle-probe pressure measurement during and after irradiation with a laser pulse of 100 mJ. The plasma-induced shock wave leads to a transmission loss of up to 45% [Fig. 3(b)]. The variation in transmission persists for a time much longer than the pressure signal. This is due to the stress-induced variations of the optical properties of the fiber. The transmission loss due to the collapse of the bubble reaches a value of up to 97% [Fig. 3(b)]. Complete destruction of the fiber is not observed in this case due to a slight misalignment between the irradiation and sensing fibers.

In Fig. 4, the pressure and transmission transients during the collapse of the first cavitation bubble are shown on an expanded scale. The pulse energy is again 100 mJ (318 J/cm^2). A pressure peak of 54 bars and a reversible transmission loss of 34% have been measured for the shock wave induced during the plasma expansion. In this case, the collapse of the cavitation bubble broke the target fiber

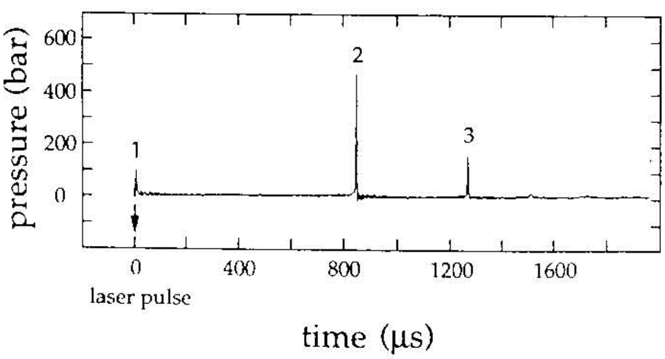

FIG. 2. Acoustic signals recorded after laser irradiation with a pulse of 2.5 μs duration and an energy of 100 mJ through a 200 μm core diameter fiber (318 J/cm^2) on a white marble model stone. The pressure detector is placed 6.5 mm away from the fiber tip. (1) Plasma-induced shock after 3.9 μs, (2) first bubble-induced shock after 870 μs, and (3) second bubble induced shock after 1.3 ms.

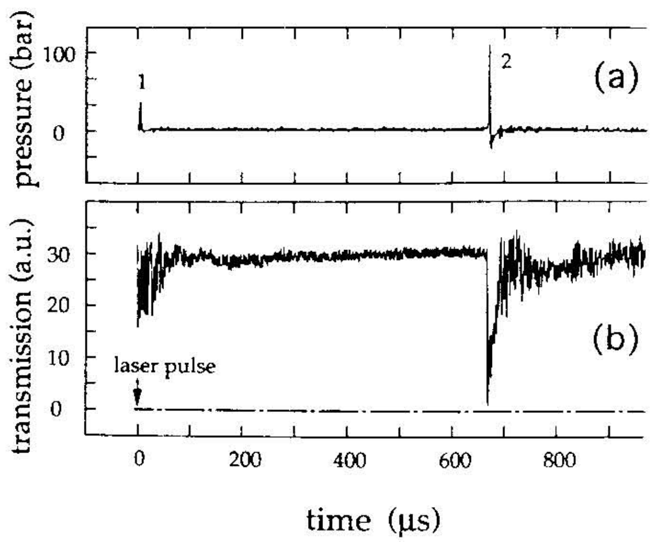

FIG. 3. Time-resolved transmission loss of a fiber with 50- and 125-μ core and cladding diameters, respectively, after laser irradiation wit pulse of 2.5-μs duration and an energy of 100 mJ through a 200-μm c diameter fiber (318 J/cm^2). (a) Acoustic signal detected 5.6 mm aw from the fiber showing the plasma induced shock (1) and the cavitat bubble first collapse-induced shock (2). (b) Transmission signal of sensing fiber.

620 after laser irradiation. A slight delay of 3.5 μs t tween the optical and acoustical signals due to the prop gation time of the shock wave from the impact point to t hydrophone is observed. For the 20 fiber samples subject to such conditions, breaking occurred after the cavitati bubble collapse.

Our results on fibers demonstrate the major role of t cavitation bubble collapse for fragmentation with micr second laser pulses. The results also confirm unambig

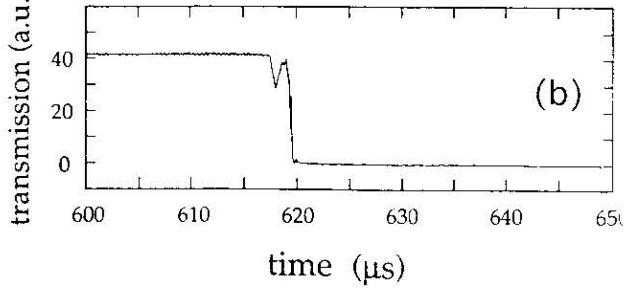

FIG. 4. Time-resolved transmission signal of a fiber with 50- and 125-μ core and cladding diameters, respectively, during bubble collapse fo laser irradiation with a pulse of 2.5-μs duration and an energy of 100 through a 200-μm core diameter fiber (318 J/cm^2). (a) Acoustic sig detected 5.8 mm away from the fiber. (b) Transmission signal of sensing fiber.

ously time-resolved flash video imaging of cavitation bubble dynamics and fragments ejection during stones fragmentation, which already suggested that fragments are ejected after the cavitation bubble collapse.[17] However, the strength of the pressure transient generated during plasma formation is strongly related to the duration of the laser pulse. This conclusion is obtained by comparing our microsecond-pulse results with the measurements published by Vogel and Lauterborn[12] with nanosecond pulses. It is, therefore, very likely that the relative mechanical strength of the plasma expansion shock and the cavitation bubble collapse shock depends on the laser pulse duration. Thus, the fragmentation mechanism observed here for irradiation with microsecond pulses cannot be generalized to the case of shorter pulse durations.

In conclusion, the previously accepted description of pulsed dye-laser lithotripsy, which refers to the plasma expansion acoustic shock for the origin of the fragmentation process, has to be revised. Although the occasional appearance of tiny fragments cannot be excluded in response to the plasma expansion shock, microsecond pulse laser fragmentation is clearly induced by the cavitation bubble collapse.

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