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STUDY OF THE MECHANISM OF LASER-BASED LITHOTRIPSY USING OPTICAL TECHNIQUES

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Phenomena relevant to fragmentation of gallbladder stone during a pulsed laser action were studied. Real conditions have been simulated. A stone was immersed in distilled water and laser energy was delivered to its surface by an optical fiber. Two different cases were studied: when the tip of the fiber was in contact with the stone and when it was at a distance from it. Using ultra-fast shadowgraphy and interferometry, mechanism of destruction of a stone due to laser-based lithotripsy was studied.

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1. Introduction

Lasers have been used in medical therapy and diagnostics for almost thirty years [1–3]. They include laser lithotripsy, photodynamic therapy, laser destruction of bladder tumors, etc. Recent improvements in laparascopy, retroperinoescopy and endoscopy in general, make internal organs visually accessible. These treatments rely on the fiber-optics laser-light delivery. In this work, we study the use of laser energy delivered via optical fibers for the destruction of stones formed in internal organs. The laser lithotripsy of the gallbladder or other stones (formed in other organs) has a potential to become a very attractive technique: less invasive, less risky and of a low cost compared to the conventional operation. The laser lithotripsy is not the standard procedure or technique yet. The main reason for this is the difficulty to access to the gallbladder using fiber or endoscopic techniques. The proper orientation of the fiber towards the stone during the laser action and rejection of the tissue of the organ is another problem. The mechanism of stone destruction during the laser pulse action is not yet fully understood. Several theories have been reported which are meant to explain this mechanism. These theories can be grouped on the basis of two possible mechanisms. First, it is thought that the cause of destruction during a laser pulse action is of thermo-chemical nature [4–6]. Secondly, the opto-mechanical effect of the laser action is considered to be responsible for the stone destruction [7–11]. These two mechanisms are considered mutually exclusive.

In this work, using optical techniques, we studied the mechanism of the gallbladder stone fragmentation when laser lithotripsy is applied. In Sect. 2, materials and methods are presented. The shadowgraphy is introduced to study the mechanism causing the stone destruction during the action of a Ho:YAG laser-pulse.

In Sect. 3, results obtained using shadowgraphy are presented. The effects of laser pulse for two positions of the tip of the optical fiber are evaluated. Two cases are studied: When the tip of the fiber was touching the surface of the stone and when it was at a distance from its surface.

Interferometry is proven to be an appropriate technique for biomedical applications [12–15]. In Sects. 3.1 and 3.2, we describe the application of interferometry to study the ultra-fast phenomena occurring between the fiber and the surface of the stone during the laser action when the tip of the fiber was at some distance from its surface. The interpretation of the interferograms is made. The blurred space between the stone and the tip of the fiber is visualized. Section 4 presents a conclusion.

2. *Materials and methods*

To monitor the dynamics of laser lithotripsy of gallbladder stones, ultra-fast photography was applied. The gallbladder calculi were obtained from a stone analysis laboratory (Mubarak Hospital in Kuwait). The experiments were performed with a Ho:YAG medical laser ($\lambda = 2.12$ μm, pulse duration 250 μs). A 350 μm diameter optical fiber was used. Actual conditions inside a gallbladder were simulated during the stone fragmentation. The calculus was placed in a water-filled glass cuvette at room temperature. The experimental setup is shown in Fig. 1a and the ballistic image of the stone is shown in Fig. 1b.

One end (the tip) of an optical fiber was placed on top of a stone under investigation. The position was adjusted with a homemade mechanical device, which is provided with a scale to allow the determination of the distance from the stone. The other end of the fiber was connected to a Ho:YAG laser delivering the pulsed power to the stone. The stone, laser pulse action and other phenomena were illuminated with a N-Dye Laser (its pulse duration was 7 ns). The experiment was performed in a dark room where a camera placed at a distance from the cuvette with its "open mouth" recorded all phenomena. The shadowgraph of the stone and induced phenomena during the Ho:YAG laser-pulse action is shown in the Fig. 1c. An electronic system consisting of an electronic circuit, delay generator, general purpose interface bus IEEE-488 (GPIB),

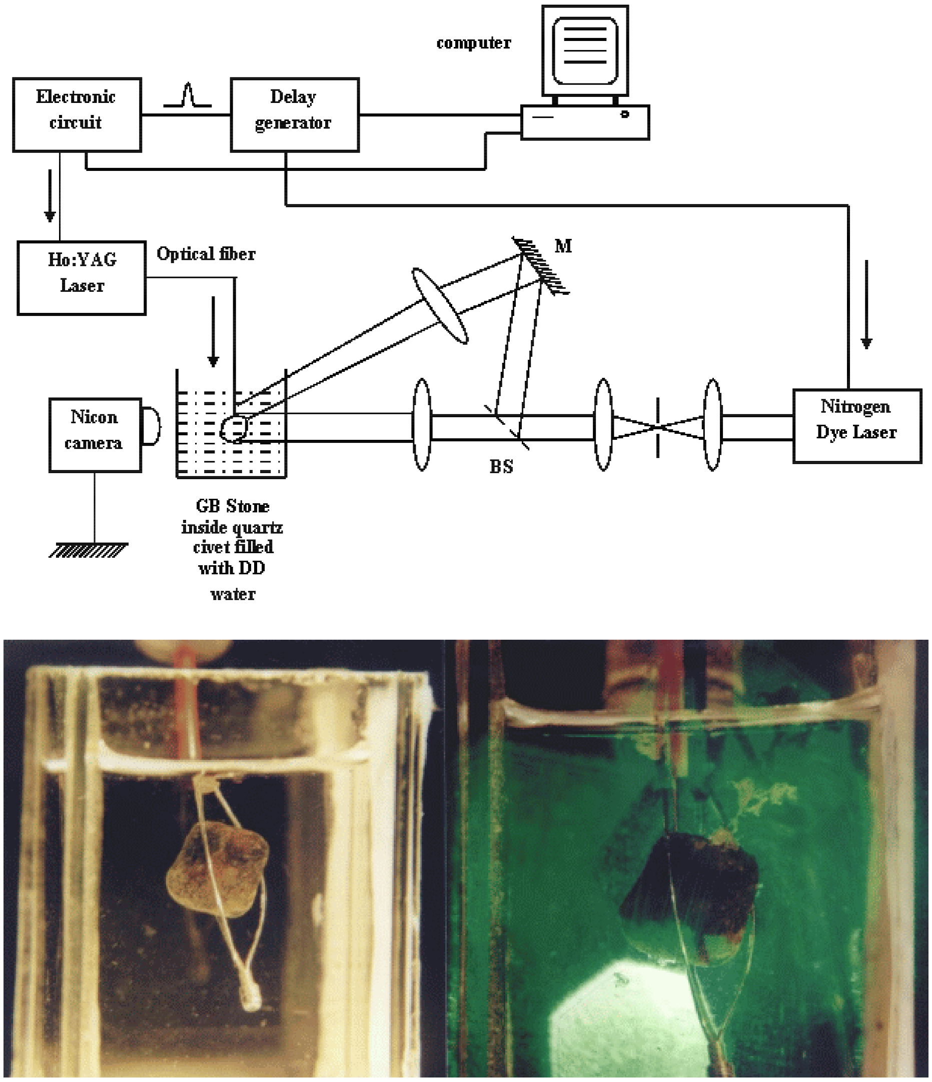

Fig. 1. (top) The experimental setup for shadowgraphy. (bottom left) Photograph of the stone. (bottom right) The shadowgraph of the stone made with a 7 ns *N-Dye laser pulse.*

computer and data acquisition board along with a program written in Quick Basic were used to trigger the pulses of both lasers.

Ho:YAG laser was triggered by a home-made electronic circuit which consists of a divide by 21 counters. The counter takes input from the laser flash lamp and waits until the laser energy is stable and attained the required preset energy per pulse. Once this condition is achieved, this circuit gives a 30 ms pulse before the next laser shot and stops the laser from further firing. Single shots were delivered from this laser, which has a minimum frequency of 5 Hz. The output pulse from the triggering circuit is fed to a delay generator (DG 535, Stanford Research Systems) in order to start the N-Dye laser (used as a flash source) with a variable delay with respect to the Ho:YAG laser pulse. All these operations including the control of electronic circuit, delay generator, firing of Ho:YAG laser, firing of N-Dye laser and the data acquisition in computer are controlled by the National Instruments GPIB and data acquisition board in a PC, along with a program written in Quick Basic.

The main goal of the experiment was to monitor the dynamics of the phenomena during the Ho:YAG laser pulse action (duration of 250 μs). This should be achieved by taking many photographs within the span of 250 μs. In the absence of that technology, an indirect approach was applied. It has been experimentally confirmed that in the working regime of the Ho:YAG laser, when single pulses are fired with variable delays, the pulses are repeatedly the same and of nearly constant power during a pulse. The electronic system described above was used to fire the N-Dye laser pulses with variable delays during the Ho:YAG laser pulse. Actually, this was performed by firing first the Ho:YAG laser pulse, and at the same instant, the N-Dye laser pulse was fired as well, and the first photograph was taken. The second photograph was taken when the firing moment of the N-Dye laser was delayed by 20 μs. This procedure continued until a complete scanning of the Ho:YAG laser-pulse action was photographed.

To obtain good photographs, the output beam from the N-Dye laser was expanded and optically filtered with a spatial filter (Newport product) and a diaphragm placed at the focal point of the objective, as shown in Fig. 1a. A lens was placed on the left side of the focal point at the appropriate distance making the output beam expanded and parallel. By using a beam splitter, this beam was divided into two parts. The main part of light, after passing through a lens, was used to illuminate the whole stone and surrounding space. This was projected by the objective of a camera where the shadowgram was obtained. The space above the top of the stone was illuminated with the beam, which was reflected by a mirror. The shadowgram obtained with this beam was used for the interferometry investigation. The duration of Ho:YAG pulse was 250 μs, and the duration of the pulse used as the illuminating source for ultra-fast photography was 7 ns. Therefore, during the time of the Ho:YAG laser pulse, many photographs can be made. The increase of delay between two consecutive N-Dye laser pulses was selected to be 20 μm. Hence, the dynamics of the phenomena occurring during the laser action could be studied with a very good time resolution.

3. *Results*

Figures 2a, b and c show the results of the shadowgraphy by the described procedure. Each image (shadowgraph) was obtained during the exposure time (7 ns) of the illuminating N-Dye laser. As can be seen, the tip of the fiber was touching the surface of the stone. The upper surface of the stone was polished before the

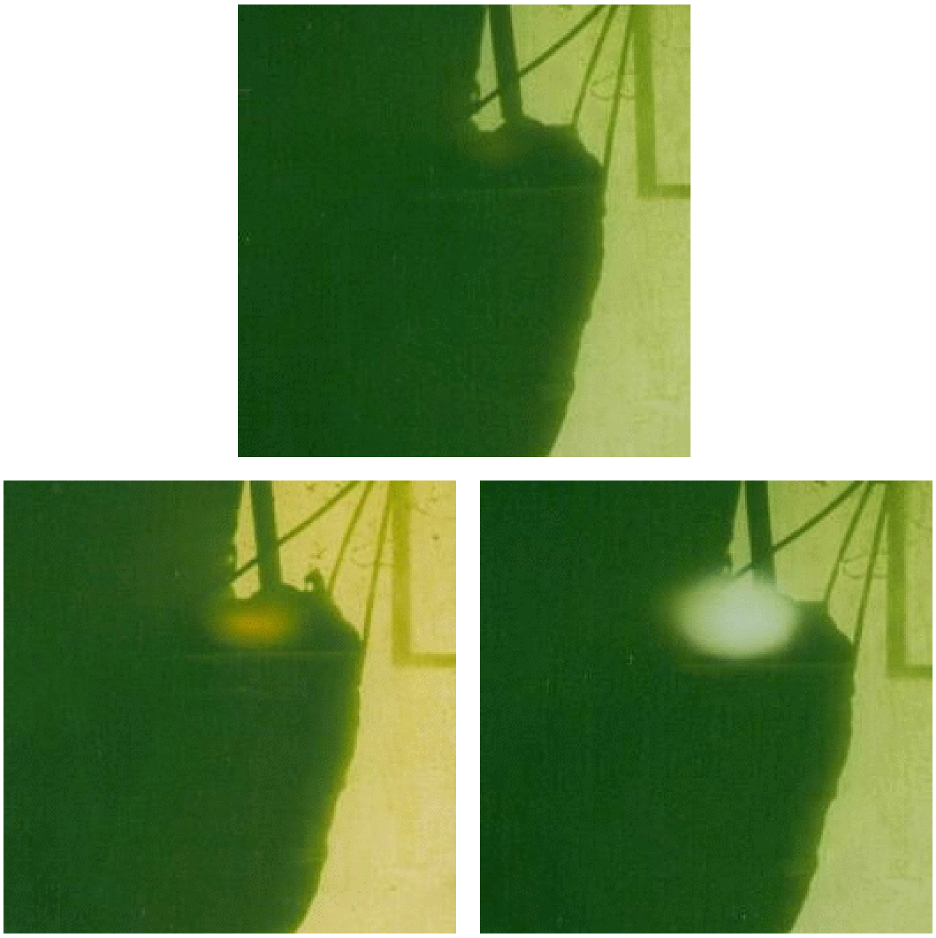

Fig. 2. Time-resolved shadowgraphy when the tip of the fiber was touching the surface of the stone.

experiment was made. In the first image (Fig. 2a), the swelled convex meniscus of the surfaces during the laser action can be seen. In Fig. 2b, a clear thermal effect of the laser action can be seen. In Fig. 2c, plasma formed in the shape of an ellipse is seen. These three figures indicate the thermo–chemical effect as the relevant mechanism.

During the second phase of the experiment, a new stone was used, and the tip of the fiber is placed 7 mm above its surface. Other experimental conditions were kept the same. The aim of this part of the experiment was to study the phenomena due to the laser pulse action when the tip of the fiber is kept at a distance from the surface [16–19] of the stone. The results obtained in this case are shown in

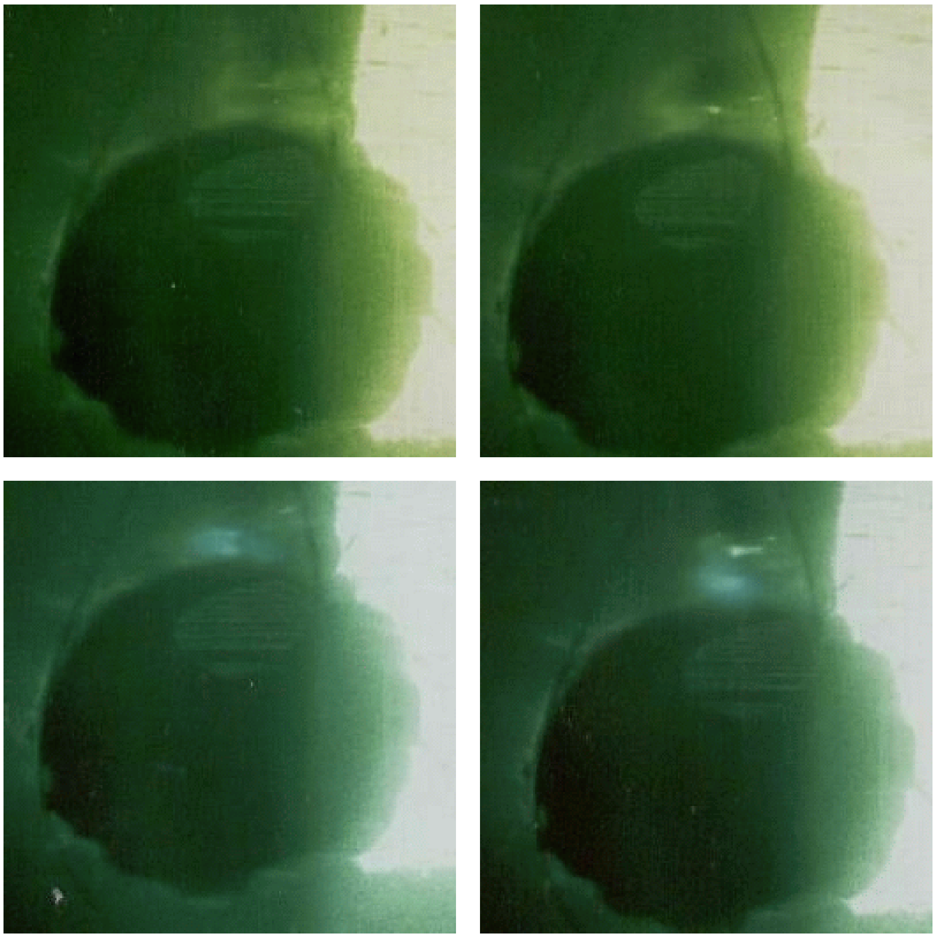

Fig. 3. Time-resolved shadowgraphy when the tip of the fiber was at the distance of 7 mm *from the stone.*

Figs. 3a, b, c and d. These images represent the time-resolved, ultra-fast phenomena obtained during the 250 μs Ho:YAG laser pulse. In all four images, the shadow of the stone with its clear contours can be seen. The shadow of the fiber and parts of the basket can also be seen.

As can be seen from Fig. 3a, a direct thermal action of the Ho:YAG laser pulse cannot reach the surface of the stone. Between the tip of the fiber and the stone there is water, which absorbs the laser energy. Therefore, the claim that thermo-chemical effect is not the cause of the damage to the stone seems to be correct under these conditions. The concentrated energy causes a rapid evaporation of the fluid. The pressure action at this point generates a bubble between the tip of the fiber and the stone, which can be seen in Fig. 3a. In the following instants (Figs. 3b–d), new dynamic events occur. It should be pointed out that bubble formation and collapse has a strong impact on the stone, which eventually leads to its destruction. The shape and size of the bubble and fluid distribution at its contours determine the amount of the density of energy or pressure released during its collapse. From Figs. 3a–d, it is not possible to describe the shapes and their change with a high degree of certainty. The only obvious observation is that between the tip of the fiber and the surface of the stone a very blurred and undefined shape is formed.

The mechanism of bubble formation is considered elsewhere [3]. Several techniques for the investigation of the bubble have been reported [10]. In the next section, a new technique for the investigation of the bubble formation will be presented. This method is based on the interferometry and fringe interpretation.

3.1. Investigation of the bubble using interferometry

Using conventional shadowgraphy, as is shown in Figs. 3a–d, a shadow of the stone of a shape of a black ball with its clear contours was obtained. As mentioned above, the information about the bubble formed above the stone is blurred and unreliable to make any conclusions. Nor is it possible to monitor the changes of its shape in time. To improve the observations, another coherent beam was introduced besides the main beam. This additional beam, by passing through the bubble, was reaching the black part where the shadowgraph was formed. The black part of the shadow of the stone was used as a screen for the projection of the interferogram of the bubble. The formation of the interferogram is based on the diffraction of the coherent laser beam in an optically transparent bubble. Namely, in the transmitted coherent beam through the body of the bubble, phase changes are introduced. One could say, the transmitted laser beam has registered information about the bubble. The phase changes are due to the density distribution within the bubble. Thus, the interferometric image is formed and projected on the black part of the image (dark shadow of the stone). The phase distribution of the coherent beam, the shape and information on the hydrodynamic state of the bubble at this point is encoded and projected in the shape of an interferometric pattern. The obtained patterns are shown in interference images in Figs. 3a-d.

3.2. Fringe interpretation using image processing

The parts of the images where the fringe patterns are located were selected and cropped using an image processing software, which was adapted for this particular case. They are shown in the left panels of Figs. 4a-d. The fringe patterns, as shown in the figures, are horizontal and parallel. These shapes have an appropriate fringe distribution for tracing of their centres and performing fringe analysis. In order to obtain a reliable comparison between the selected (cropped) fringe patterns and to quantify and monitor their change at different moments in time, the size of the analyzed patterns was limited to a circle (as is seen in Figs. 4a-d, left panels). In

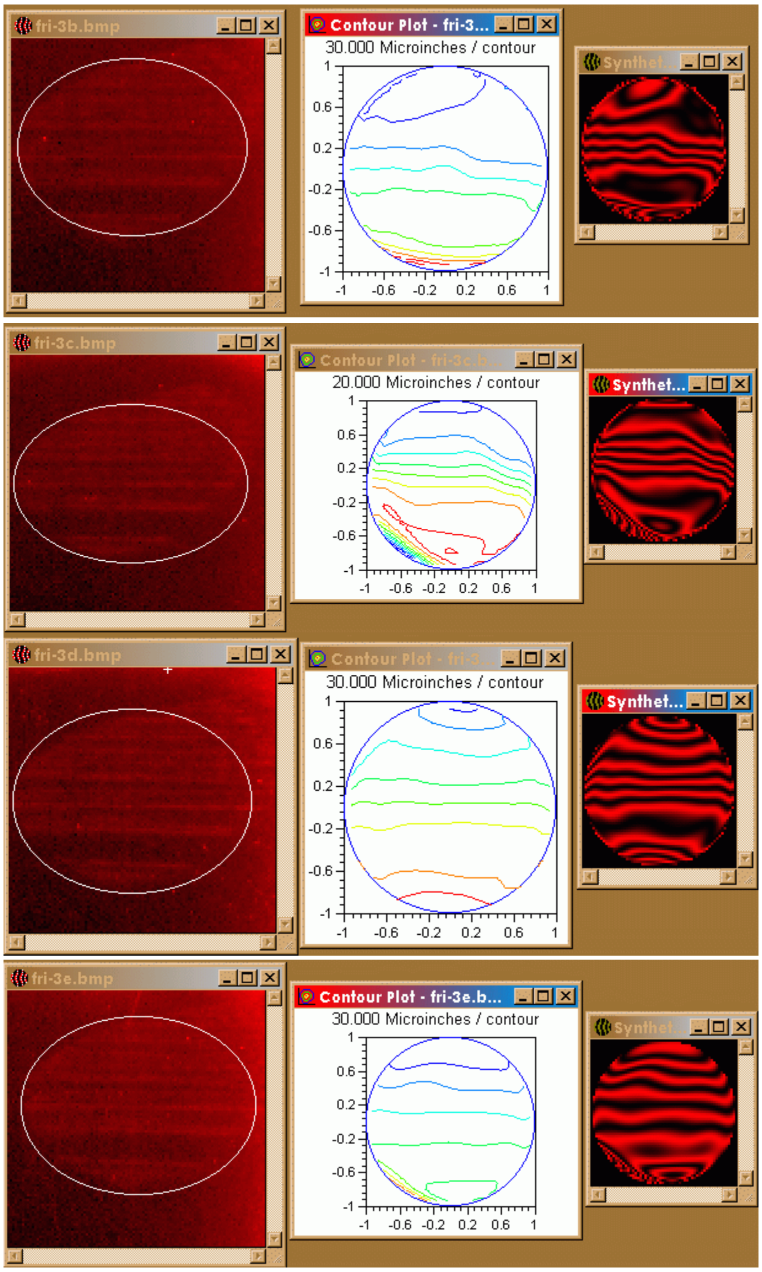

Fig. 4. Fringe interpretation.

the four cases, the radius of the circular border was the same, i.e. the selected sizes were the same.

The selected interferograms shown in the left panels were processed using the fringe analysis software. The synthetic analyses were performed and the results are shown in the right columns of Figs. 4a–d. The contour representations, shown in the middle columns of Figs. 4a–d, are very clear. While from the interferometric patterns alone, it was very hard or impossible to make distinctions between the patterns, after the fringe analysis was performed, clear outputs shown in the middle and right panels of Figs. 3a–d were obtained.

The obtained results of the fringe interpretation have revealed several features and have demonstrated the evolution of the bubbles in time. This is an important feature of synthetic fringe presentation, as evidenced in each of Figs. 3a–d.

As is seen from the figures, they represent the fluid distribution in the bubble (whose lifetime is very short). It should be pointed out that the shapes of laser-induced bubbles have been studied before, however, here, by using fringe analysis technique, the monitoring of the dynamics of the bubble morphology and its evolution within an ultra-short time (duration of the Ho:YAG laser pulse) is achieved. Quantified analysis can also be performed, which remains a task of our future work.

4. *Conclusion*

The dynamics of the phenomena and processes taking place during the laser lithotripsy have been studied by ultra-fast shadowgraphy. The main goal of the experiment was to understand the mechanism of the stone destruction and associated phenomena during a laser-pulse action. Results obtained when the tip of the fiber was in contact with the stone indicated that the thermo-chemical process takes place, and is the main cause of the stone fragmentation. The studies and results obtained when the tip of the fiber is at a certain distance from the stone that was immersed in water have indicated that opto-mechanical process take place. In that case, a bubble formation above the stone takes place.

Using an interferomeric technique and fringe analysis and interpretation, the formation of the bubble and evolution of its morphology during the laser pulse action was monitored. That proved to be a major improvement in the observations of evolution of the bubbles. The study and results revealed that the thermo-chemical process is the main mechanism of laser lithotripsy. However, opto-mechanical effect should not be excluded for a certain position of the fiber and when the stone is immersed in a fluid. The fluid cools down the space between the stone and tip of the fiber by absorbing the energy during the laser action. Therefore, the main conclusion is that both the thermo-chemical and opto-mechanical processes can take place during the laser-pulse action and stone fragmentation.

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PROUČAVANJE MEHANIZMA LASERSKE LITOTRIPSIJE OPTIČKIM TEHNIKAMA

Proučavamo pojave razbijanja žućnog kamena tijekom djelovanja laserskog impulsa. Oponašali smo stvarne uvjete kamena stavljanjem u destiliranu vodu, a lasersku energiju prenosili smo na njegovu površinu optičkom niti. Razmatrali smo dva slučaja: vrh niti u dodiru s kamenom i na nekoj udaljenosti od kamena. Primijenili smo metodu fotografije sjena i interferometriju za proučavanje mehanizma razbijanja kamena laserskom litotripsijom.