Optics and Lasers in Engineering 46 (2008) 535–540

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Optical investigation of dynamics of phenomena of laser-based lithotripsy

Jahja Kokaj *, Mustafa Marafi, J. Mathew

Department of Physics, Kuwait University, P.O. Box 5969, Safat 10360, Kuwait

ARTICLE INFO

Article history:
Received 8 March 2007
Received in revised form
1 December 2007
Accepted 25 February 2008
Available online 16 April 2008

Keywords:
Laser lithotripsy
Gallbladder stone
Bubble
Mathematical morphology

ABSTRACT

Using time-resolved high-speed shadowgraphy, the dynamics of phenomena due to laser-based lithotripsy is studied. Collapsing mechanism of bubble formed therein is investigated. In order to study the mechanism, the optically implemented mathematical morphology is applied. The study of the shape of the plasma and the collapsing region of the bubble of fluid that we are studying can possibly be used for practical application for laser-based lithotripsy.

1. Introduction

Laser lithotripsy is considered to be a most convenient, economical and less painful technique for destruction of stones formed in human body. A very thin optical fiber can transport the laser energy to the stones formed in the gallbladder or kidney, destroying them within a short time. However, removal of stones still requires, for the method based upon laser-based lithotripsy has not yet become practically operational. Still a conventional operation or a total extraction of gallbladder is a common procedure. The main reason for this is that phenomena and dynamics in the laser lithotripsy process are not fully understood [1–8]. Most of our present understanding of this dynamics has come from high-speed photography, shadowgraphy and spectroscopic studies [4] of the spatial and temporal evolution of phenomena during laser ablation and lithotripsy. According to present understanding, when laser energy delivered by the fiber is released at the end of the fiber, laser-induced breakdown (LIB) occurs and plasma is formed. Plasma is defined as a medium consisting of neutral atoms, electrons, ions and quanta emitted from atoms or ions. The plasma is formed due to avalanche effect which can be explained through the following mechanism: looking at its quantum mechanically, the laser beam constitutes a photon flux. At a high photon flux there is a considerable acceleration of electrons. Consequently, electrons are accelerated by inverse bremsstrahlung. A free electron collides with an ion or an atom and absorbs photons in doing so. The electron gains energy and is accelerated. When their energy is large enough, additional electrons are stripped-off when they collide with atoms. The new electrons are then also accelerated and the number of free electrons increases in an avalanche fashion. This ionization process is based on the presence of several photons simultaneously i.e. the process is based on multi-photon ionization caused by a photon flux arising from the laser beam. Upon the plasma production the temperature rises rapidly. The incoming laser power during a particular pulse increases the energy of plasma and consequently the temperature increases rapidly, reaching several thousand Kelvin. This causes rapid evaporation of the fluid thus generating a bubble. The pressure inside the bubble increases until the pulsed laser power is feeding the system. Since the lifetime of the laser pulse is short, of 250 μs duration, instantaneously will be no energy available to feed the system. Accordingly, the outward pressure inside the bubble will cease to exist. Under the hydrostatic pressure of the surrounding fluid, the bubble will collapse releasing very high energy. Since the surroundings fluid of the bubble is homogenous, the shape of the plasma or distribution of the temperature and the shape of the bubble are homologous.

It is shown in the literature that in the use of laser power, cavitation bubbles are understood to be the driving force for cutting a tissue and destroying a stone [7–9].

As described above such bubbles result from an explosive evaporation of water due to dielectric breakdown [10–18] or radiation absorption in water [18,19] or tissue [20–23].

In Section 2, the experimental setup and the procedure measurement are described. Results obtained in reflection mode by shadowgraphy are presented as well. In Section 3, the results of the bubble-shaped plasma obtained by using time-resolved shadowgraphy are shown. Results showing collapsing mechanism of a fluid bubble, investigated by optically implemented mathematical

* Corresponding author. Tel.: +965 7136048; fax: +965 5624520.
E-mail address: kokay@kuc01.kuniv.edu.kw (J. Kokaj).

0143-8166/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.optlaseng.2008.02.006

morphology (MM), are presented in Section 4. Investigation of a bubble using optically implemented MM is presented in Section 5. The conclusion is presented in the last section.

2. The experimental setup

We perform ultra-fast photography to monitor the dynamics of laser lithotripsy of gallbladder stones. The experimental setup of this method is shown in Fig. 1.

A gallbladder stone was placed in water-filled glass civet at room temperature. The tip of an optical fiber is controlled by a homemade mechanical device. This is provided with a scale to measure accurate distance between the fiber tip and the surface of the stone under investigation. The other end of the fiber is connected to a Ho:YAG laser which delivers the pulsed power to the stone. The diameter of the core of the fiber is 200 μm. The stone and the phenomena generated during the action of Ho:YAG laser pulse for fragmentation are illuminated with a 9 ns pulse from a N-DYE laser. The experiment is performed in a dark room where a camera is placed at a distance of 5 cm from the civet with its shutter open to record all the phenomena. In order to obtain a better resolution, a microscope is used to magnify the image which is recorded by the camera. The system consists of an electronic circuit, delay generator, oscilloscope, GPIB, computer and a data acquisition board. The program written in quick BASIC is used to trigger the action of both lasers.

3. High-speed imaging of a bubble

The images obtained, using the above described setup and procedure, are shown in Fig. 2. The high-speed photograph obtained in the reflection mode by illumination of 9 ns N-Dye laser pulse is shown in Fig. 2a.

In Fig. 2b, a shadowgram representing an illustrative example of the shadowgraph of the optical phenomena akin to the laser lithotripsy is shown. Here the shadow of a stone held by a holder, the optical fiber and plasma in the shape of a bubble can be seen.

In the past several factors causing the lithotripsy have been addressed [25,26]. We have been able to capture simultaneous appearance of all mentioned phenomena in the same image, interferometry was used to visualize and study the shadowgraphs of the stones and tissue [24].

In our earlier paper, fluorescence spectroscopy was used to study stone, tissue and bile. On the other hand, in our present paper we use the time-resolved high-speed imaging in order to study the phenomena and mechanism for stone destruction.

The ballistic and fluorescent images were measured and studied in order to perform the correlation and recognition of the target to be destroyed and to reject the tissue, when the tip of the fiber used to guide the laser power is not properly oriented [26].

Here, we try to get insight into the dynamics of formation and development of a bubble that has an important role in destruction of gallbladder or kidney stones when the laser power is used. Therefore, evolution of the bubble during the action of a laser pulse is addressed in the present work.

4. The shape and dynamics of the bubble

In order to achieve faster and accurate stone destruction during the laser lithotripsy, an optimal arrangement of experimental factors is required. In the phenomenon associated with the destruction of the stone, formation of plasma, a bubble, its

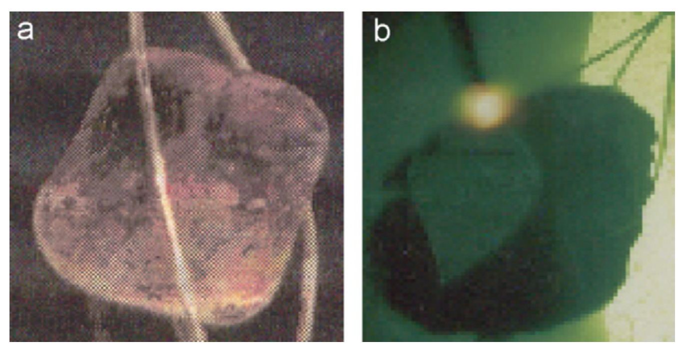

Fig. 2. The photograph of the stone obtained in reflection mode by conventional high-speed photography and a shadowgraph of the stone, fiber and plasma in the shape of a bubble. (a) The photograph of a bubble obtained in the reflection mode, (b) the shadowgraph of a stone, the fiber and plasma in the shape of a bubble.

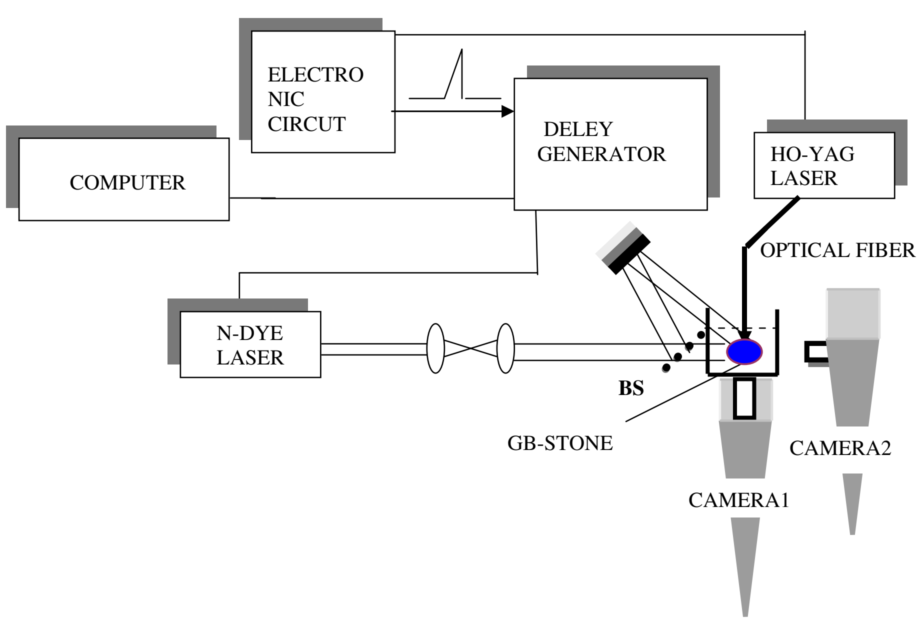

Fig. 1. The experimental setup.