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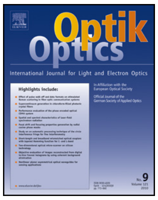

Time-resolved digital holographic diagnosis of the shock wave in water induced by femtosecond laser pulse

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ABSTRACT

Pump-probe technique is employed to investigate the dynamic process of shock wave in water induced by femtosecond laser pulse. The time resolved shadowgraphs and holograms were obtained experimentally, and the 2-dimensional phase maps were reconstructed from holograms. From the analysis of the phase maps, the evolution process within the laser–water interaction region was described and the formation mechanism of the shock wave was discussed.

1. Introduction

In recent years, femtosecond laser pulse [1,2] has been broadly used in medical fields, such as ophthalmology [3], neurosurgery [4] and nanodissection of human chromosomes[5]. Because biological tissue contains large amounts of water, therefore these applications require in-depth understanding of the interaction mechanisms between femtosecond laser pulse and water.

When femtosecond laser is focused in water, the high power deposited near the focus area generates multi-photon ionization and avalanche ionization [6], which leads to high temperature plasma. A shock wave is stimulated when the plasma with ultra intense pressure expands. Because the laser pulse lasts short time, plasma is cooled [6] and expansion stops quickly when no extra energy is supplemented, but the shock front separates from plasma and propagates at a speed of supersonic further before decay to sound velocity in decades of nanosecond [7]. The propagation of shock wave changes the density of water, which in a turn modulates the probe light across the region. Thus, optical method is an effective way to detect this ultrafast process. Some experiments based on optical shadowgraph have been reported. Refs. [8,9] applied the shadowgraph method to study the plasma and the shock wave front radius evolution with time and thus received the relationship between the shock wave velocity and the shock wave radius. The behavior of the shock wave induced by femtosecond laser–water interaction in the interface between air and water have been investigated using optical shadowgraph in Ref. [10], in which an aneurism-like structure, due to the quick propagation inside a hollow channel formed by laser self-focusing, is observed. As the shock wave propagation changes the refractive index of water, holography is favorable compared to the shadowgraph method. The femtosecond laser induced breakdown in water is recorded with interference method used in Ref. [11], however, the author only analyzed the bending direction and bending degree of the fringes, rather than the global phase distribution. Up to now, little details of the interaction region have been investigated, thus digital holography, which can record both amplitude and phase information globally, can be an effective tool to get more comprehensive information than optical interference [11,12] or shadowgraph.

In this paper, we combine digital holography and pump-probe technique to record the interaction region of femtosecond laser pulse and water. Two-dimensional phase maps of the plasma and shock wave are obtained. The evolution process and formation mechanism of shock wave induced by femtosecond laser pulse are discussed by analyzing the phase value and structure in time sequence phase maps.

2. Experimental setup

The experimental setup is shown in Fig. 1. A single 50 fs laser pulse with central wavelength of 800 nm was divided into a pump pulse and a recording pulse by a beam splitter BS_1. The pump pulse with peak power of 76 MW was focused by a 10× microscope objective (NA = 0.25) on water. The recording pulse was frequency

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doubled by a BBO crystal and divided into a probe beam and a reference beam by BS_2. A 4f system consisting of lens L_1 ($f = 15$ mm) and L_2 ($f = 300$ mm) was employed in the probe beam to obtain amplified object images. The image plane hologram was recorded by a CCD (MINTRON 1881EX, 8.3 μm × 8.3 μm, 768 (H) × 576 (V)). To avoid the disturbance of the pump light, a 400 nm band pass filter was placed in front of the CCD. When the reference beam was cut off, shadowgraphs could be recorded. By changing the relative path difference between DL_1 and DL_2, a set of shadowgraphs or holograms at different time delay could be recorded.

3. Results and discussions

Fig. 2 shows a sequence of time-resolved shadowgraphs taken at different delay times during the interaction between the femtosecond laser pulse and the water. It can be seen in Fig. 2 that the femtosecond laser–water interaction region mainly consists of two parts: the breakdown region in the central and the surrounding shock wave front. Due to Rayleigh length of Gaussian beam and self phase modulation effect of the focused femtosecond laser pulse, the breakdown region is a filament spot rather than a spherical spot. Therefore the shock wave front generated by the breakdown in water is cylindrical and the axis of pump light is the axis of the shock wave front.

To further investigate the dynamic process, the time sequence holograms corresponding to the shadowgraphs in Fig. 2 were recorded, as shown in Fig. 3, from which the phase difference of the probe beam and the reference beam is derived as shown in Fig. 4. In our detecting mechanism, the probe beam propagated twice through the shock wave, thus the phase value in Fig. 4 is the summation of phase difference along the probe path. The positive or the negative values of the phase difference refers to the situation when the refractive index was smaller than or larger than that of undisturbed water in our analysis.

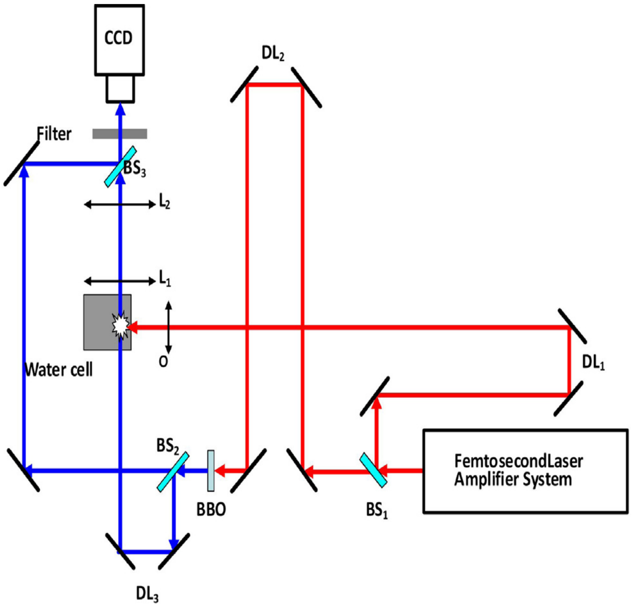

Fig. 1. The experimental setup.

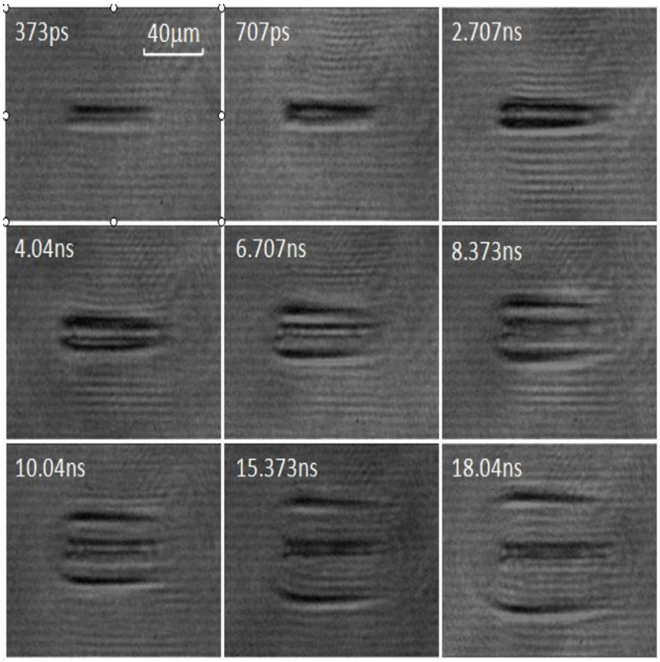

Fig. 2. The time resolved shadowgraphs.

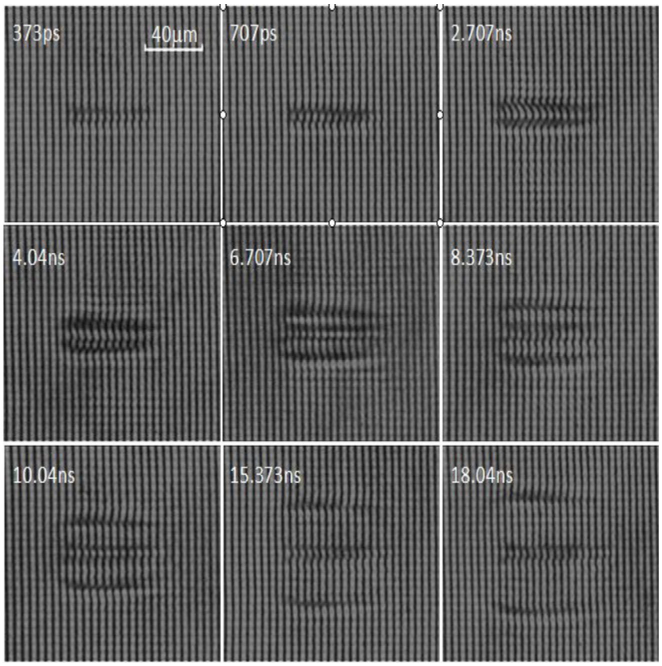

Fig. 3. The time resolved digital holograms.

The phase maps in Fig. 4 reflect the evolution process intuitively. In the first phase map recorded with the delay time of 373 ps, a positive phase region can be seen in the center, which corresponds to the laser induced breakdown of water and the formation of plasma. A negative phase region whose value is about -0.5 rad was generated, which is the shock wave front. At 707 ps, the phase value in plasma region reaches the maximum in all phase maps, but the shock wave front is still in the vicinity of the plasma rim. When the delay time was 2.707 ns, the phase value in plasma region became negative, which means that the change of the refractive index induced by shock wave is stronger than that by the plasma. Thus, the region surrounded by the shock wave front forms an “intermediate area” [9] with a negative phase. In the radial direction the shock wave front separates from plasma rim; in the axial direction the shock wave fronts on both the front and the back terminals of the plasma region appear. Thus, shock wave fronts on both the radial direction and the axial direction mix as a whole. It is noticed that a wedge division structure appears on the tail of the plasma. At 4.04 ns, the intermediate negative phase region continues