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Evolution of shock waves formed by laser-induced breakdown in air*

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The evolution of shock waves produced by 7 ns laser pulses in air is investigated by time-resolved shadowgraph. A nodular structure of the shock wave is observed. It is found that the origin of the structure is the multi-longitudinal-microfocus caused by the astigmatism of the laser beam. The spherical shock waves formed by each microfocus expand gradually and collide with each other, resulting in the nodular structure of the shock wave.

Keywords: shock wave, nodular structure, astigmatism
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1. Introduction

The interaction of high-intensity laser pulses with matter can lead to the generation of dielectric breakdown through optical absorption, laser-induced breakdown (LIB). The plasmas induced by LIB have important applications in the fields of laser propulsion,[1−4] laser-induced ignition[5,6] and medical science.[7−9] There have been many researches on LIB, such as the threshold,[10] energy absorption[11] and the profile of the laser-induced shock waves.[12−15] The LIB-induced plasma has a nodular structure. However, the formation process of the nodular structure still has not been investigated in detail. In this paper, we study the formation and evolution of the nodular structure experimentally. The origin of the structure can be attributed to multiple longitudinal microfocusing of the laser beam, caused by the beam astigmatism, and the subsequent coalescence of the shock regions. Our results suggest that the process of formation and evolution of the shock wave deserves more detailed theoretical and experimental study, as it determines the efficiency of most applications of LIB.

2. Experimental setup

The experimental setup is shown in Fig.1. A laser beam from a Q-switched Nd:YAG laser system, operated at $\lambda = 532\,\text{nm}$ and 1.4 J maximum energy in a 7 ns pulse, is sent through a beam splitter (transmission = 30%, reflection = 70%) and is split into a pump and a probe beams. The pump beam with 70% laser beam energy is focused by a plano-convex lens with a 125 mm focal length to produce air breakdown.

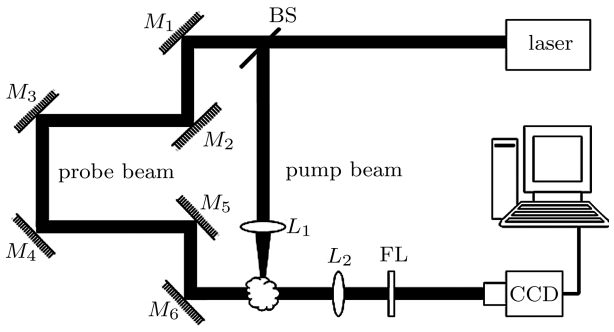


Fig.1. Experimental setup for shadowgraph of shock waves. M = mirror, BS = beam splitter, L = lens, FL = filter.

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The probe beam is used to observe the optical breakdown in a plane perpendicular to the direction of the pump beam. The shock wave is imaged on a CCD camera. In order to obtain the temporal resolution of the shock wave, a delay line (consisting of M_2, M_3, M_4 and M_5) is inserted into the path of the probe beam, thus allowing variation of the time delay Δt between the pump and the probe pulses from 0 to 62.8 ns with 7 ns resolution.

3. Result and discussion

A typical image of the shock wave in air at 12.8 ns is shown in Fig.2 for a 500 mJ pump pulse with an intensity of $2.28 \times 10^{11}\,\mathrm{W/cm^2}$. The pump beam is incident from the right. The right side of the shock wave is darker because most of the laser energy is deposited there (plasma shielding),[16] leading to a high density plasma. The image is separated into several parts, or has a nodular structure. The reproducibility of the structure is good.

To understand the generation mechanism of the nodular structure, the temporal evolution of the shock waves is observed for different delay times and beam astigmatism. We find that the nodular structure can be easily controlled by changing the angle between the axis of the focusing lens and the laser axis.

Figure 3 shows the structure of the shock wave for different beam astigmatism at 19.7 ns. The astigmatism is produced by tilting the focusing lens to an appropriate angle relative to the laser axis. The angle between the axis of the lens and the laser beam axis is varied from 0° to 4° in Figs.3(a)–3(d). In Fig.3(a), the lens is set perpendicular to the laser beam axis ($\varphi = 0°$) and no obvious nodular structure appears in the shock wave. In Fig.3(b), the angle between the axis of the lens and the laser beam axis is about 1.2°, the tip of the shock wave becomes smaller and modulated structures begin to appear. For an angle of about 2.5° in Fig.3(c), the nodular structure can be seen at the tip of the shock wave, where there are two nodules. In Fig.3(d), for an angle of about 4°, a nodular structure similar to that in Fig.2 is observed.

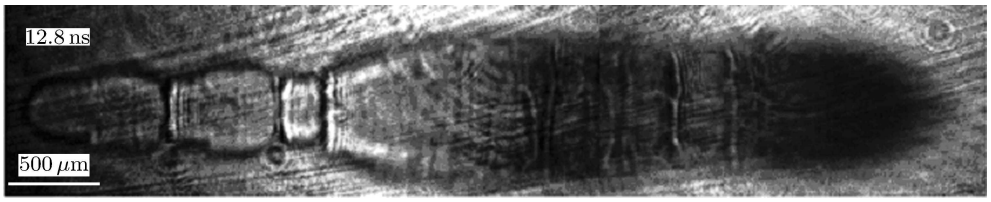


Fig.2. A typical image of the shock wave in air induced by a 7 ns pulse laser. The laser beam is incident from the right.

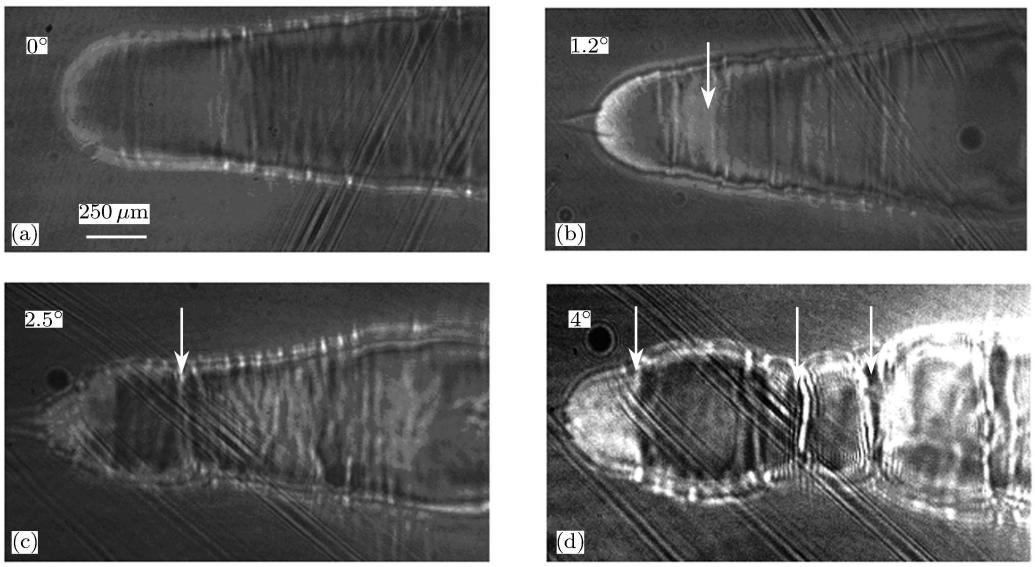


Fig.3. The structure of shock wave for different beam astigmatism at 19.7 ns. The arrows mark the nodular structure. The astigmatism was obtained by tilting the focusing lens to a certain angle relative to the laser axis. From (a) to (d), the angles between the axis of the lens and the laser beam axis are 0°, 1.2°, 2.5° and 4° respectively.

Figure 4 shows the temporal evolution of the spherical and cylindrical shock waves for an angle of 5.5°. The time delays in Figs.4(a)–4(d) are 7 ns, 19.7 ns, 42.1 ns, and 62.8 ns, respectively. One can see that when the angle between the axis of the lens and the laser beam axis is further increased to $\phi = 5.5°$, a spherical shock wave becomes detached from the global shock structure as shown in Fig.4. For this case the initial focus has broken up into a multi-microfocus because of serious astigmatism.

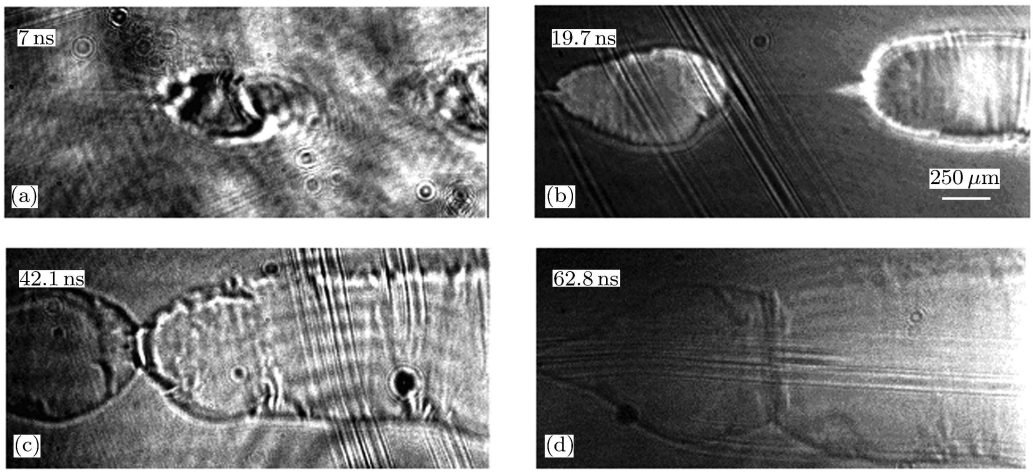


Fig.4. The time evolution process of the spherical and cylindrical shock waves from departing to colliding. The time delays in (a)–(d) are 7 ns, 19.7 ns, 42.1 ns and 62.8 ns.

At later times, the separate expanding shock regions collide with each other. The nodular structure, which is the result of the two shock collisions, is the same as that in Fig.3(d). That is, the origin of the nodular structure is the collision of the spherical shock waves formed by multiple microfocusing.

If we block the probe beam and reduce the filtering, an image of the spontaneous light emission can be seen. Figure 5 shows the image from the plasma for $\phi = 4°$. An array of separated plasmas can be observed. The bright points are well reproducible, indicating that the light is not due to the breakdown of the dusts in air but by the multiple microfocus.

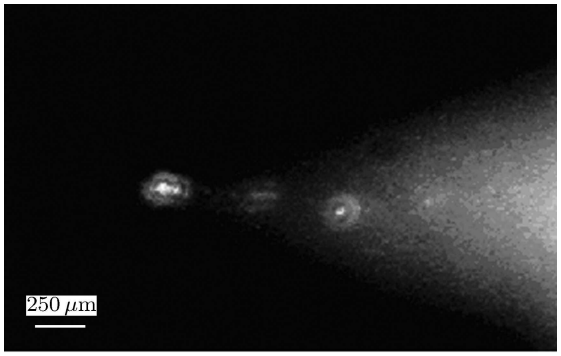


Fig.5. The spontaneous emission of plasma.

The multi-microfocusing is caused by the astigmatism. When a beam goes through a plano-convex lens, the laser beam will be focused to a line, not to a point, due to the spherical aberration.[17] The length of the focus can be estimated by the formula

$$d = \frac{\sqrt{R^2 - n^2h^2}\sqrt{R^2 - h^2} + nh^2}{n\sqrt{R^2 - h^2} - \sqrt{R^2 - n^2h^2}} - (R - \sqrt{R^2 - h^2}),$$

where d is the length of focus, R is the radius of the convex surface, h is the height from the light to the centre of the lens and n is the refractive index. The focus is estimated to be about 3.5 mm for the 20 mm diameter laser beam. This length is of the same order as the length of the shock (at 7 ns delay, the length of the shock wave is about 4 mm). When the lens is titled, the aberration induced by the lens becomes larger. This leads to less compact focusing, consisting of several individual points.[18−20] The individual spherical shock waves formed by each microfocus expand gradually and finally colloid, forming the nodular structure.

4. Conclusion

The formation of the nodular plasma shock structure in air by ns laser pulses is investigated by the

time-resolved shadowgraphy imaging method. It is found that the nodular structure is formed by multiple microfocusing of the laser beam due to astigmatism. Each microfocus ionizes the air independently, resulting in several spherical shock waves. These waves then expand and eventually collide with each other, resulting in the nodular structure of the plasma. Clearly, the formation process can determine the size and density of the plasma structure and then affect the efficiency in many applications. Thus the formation process preliminarily studied here deserves further theoretical an experimental study.

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