Formation of spiral patterns in dielectric-barrier discharge investigated by an intensified-charge coupled device

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The formation of the spiral patterns in dielectric barrier discharge is investigated through instantaneous pictures at successive driving half cycles taken by an intensified charge coupled device (ICCD). The filaments discretely distributed in each instantaneous picture corresponding to one discharge pulse indicate that they are the basic unit of the spiral patterns. An individual filament can undergo two movement states within continuous discharges: pinning at the same locations, and shifting along the arm with a small displacement (less than the filament radius), which results in the formation of the smooth arms. The averaged correlation time between the instantaneous patterns is found to be about 2 driving half cycles by the cross correlation calculations.

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I. INTRODUCTION

Research of the formation and the dynamics of spirals is one of the most striking fields in many periodic-driving nonlinear systems, such as Faraday experiments, oscillated granular layers, vertically oscillated convection, and dielectric barrier discharge [1-6]. In the past several decades, dynamic behaviors of spirals, including movements, transition mechanisms, and other prominent dynamic characteristics, have been deeply investigated on time scales much longer than the driving cycle. Recently, much attention has been paid to the study of the spiral dynamics on a time scale of one driving cycle, because it is a key step to progress towards an understanding of the intrinsic properties of spirals. Taking the agitated wet granular layer for example, it is found that similar patterns appear at every third vibration cycle, which is in contrast to the sub-harmonic patterns commonly seen in agitated dry granular matter [7]. In this paper, we report on the spatiotemporal characteristics of spirals at continuous driving half cycles in dielectric barrier discharge.

Dielectric barrier discharge (DBD) is well known for many technical applications, such as plasma display panels, industrial ozone generations, and environmental techniques [8-13]. Its devices usually consist of two parallel electrodes, at least one of them covered with dielectric materials. In the past decades, the DBD system has become an attractive pattern formation system since a variety of patterns have been observed [12-19]. Numerous complex spatiotemporal structures have been revealed through taking instantaneous pictures by intensified charge coupled devices (ICCDs) and the measurement of correlations between discharge filaments by photomultiplier tubes (PMTs) [14-19]. In recent years, research of the spatiotemporal dynamics of spirals has been a focus. In order to get to know the time-resolved dynamics of spiral patterns, it is necessary to obtain the instantaneous patterns corresponding to successive discharges. In this paper, six sequential instantaneous patterns of spirals at successive driving half-cycles in DBD are achieved by an ICCD camera, and the correlation characteristic between them is studied.

II. EXPERIMENTAL SETUP

The discharge cell is schematically shown in Fig. 1. Two cylindrical containers are filled with water and sealed with 1.5 mm thick glass plates. A metallic ring immerses in each of the containers and is connected to an ac power supply with the frequency ranging from 20 kHz to 70 kHz, so the water acts as the electrodes and the glass works as dielectric. The two containers sandwich a hollow glass plate with the inner diameter of 54 mm, which can adjust the discharge width and serve as a boundary limiting the lateral diffusion of the discharge gas. The whole cell is enclosed in a big container and filled with a mixture of argon and air. The waveform of the applied voltage is measured by a high-voltage probe (Tektronix P6015A 1000×) connecting the electrodes to a digital phosphor oscilloscope (Tektronix DPO 4104B). Pictures of patterns can be taken from the end faces of the electrodes. An ICCD camera (Pro.120PH0047) is used to record frames with short exposures. The camera has three same intensified photographing channels, each of which has two shutters. An optical beam splitter is placed between the input lens and the intensified channels. An input beam is split into three same ones by the beam splitter, and then received by each intensified channel. The six shutters in all can be triggered simultaneously, which means six frames can be obtained at one time. Through the computer-controlled software, the exposure time of each shutter can be changed, and the delay times between shutters can also be set to snap frames at different time.

III. RESULTS AND DISCUSSIONS

Figure 2 shows the images of several kinds of spiral patterns taken by an ordinary camera with a 40 ms exposure, equivalent to about thousands of times of the voltage cycle. Such patterns, behaving as several smooth curved stripes, can stay at one state for about two seconds and transform into each other at a critical voltage value, so they are called as quasi-static spirals. It is also observable that there is a complete circle surrounding each spiral pattern at the edge of the discharge area. This phenomenon should be attributed to the boundary effect, which means that discharges ignited near the boundary of the discharge area tend to arrange in shape of the boundary.

Generally, the dielectric barrier discharge is operated in a streamer discharge regime when the *pd* value (the product of gas pressure and discharge gap, 76 Torr cm in this paper) is higher than 10 Torr cm. Unlike the glow discharge, a streamer discharge is a kind of non-uniform one. When the voltage reaches the breakdown threshold, discharge events do not occur in the whole discharge area, but a few luminous discharge filaments emerge and move randomly. A filament is actually a small cylindrical discharge channel in the discharge gap. It is perpendicular to the dielectric surfaces, presenting a spot from the end view of the electrodes. With the voltage increasing gradually, filaments become more and more, interact with each other, and self-organize; finally a discharge pattern emerges. Therefore, filaments (spots seen from the end face of the electrode) are usually the basic unit of discharge patterns under the streamer mode. However, the spirals shown by long-exposure pictures in Fig. 2 are continuous stripes but not spots. The following work is devoted to make this problem clear.

The typical oscillation of the current of spiral patterns together with the applied voltage waveform is measured and presented in Fig. 3. Obviously, there is only one single current pulse superimposed on the same phase of the sinusoidal displacement current in each half cycle of the applied voltage. From the magnified image, the current pulse width is about 100 ns.

In order to know the formation of the spirals in DBD, the pictures of the spiral with different exposure times are taken by the three channels of the ICCD camera in the single shutter mode, which are triggered synchronously. Figure 4 gives the pictures of the spiral with the exposure times of 200 μs, 48 μs, and 8 μs (one half cycle of the applied voltage), respectively. One can clearly see that it is a spiral with counterclockwise winding in the picture with the exposure time much longer than one half cycle of the applied voltage [Fig. 4(a)], whereas, several filaments emerge in the picture exposed over about one half cycle of the applied voltage [Fig. 4(c)]. By comparing Fig. 4(c) with Fig. 4(a), it can also be found that the locations of these filaments are on the paths of the spiral arms in Fig. 4(a). This phenomenon indicates that the spiral in this discharge condition is composed of filaments, namely, the basic units of the spiral pattern are also filaments. For convenience, a picture exposed over one half cycle of the applied voltage like Fig. 4(c) is named as an instantaneous pattern in the following. Lengthening the exposure time to 48 μs (about six half cycles of the applied voltage), the filament footprints along the spiral arm appear [Fig. 4(b)], which indicates that the filaments move along the spiral. Noting that the pictures with different exposure times in Fig. 4 are trigged synchronously, it can be supposed that the footprints of the filaments increase with time so that they compose a spiral.

In order to study the time-resolved dynamics of the spiral pattern and to demonstrate the above supposition, the spiral pattern is investigated on a short time scale of one half voltage cycle. The discharge pictures corresponding to six successive single current pulses are obtained by three channels of the ICCD camera in the double shutter mode, as shown in Fig. 5. The six instantaneous patterns are taken one after another with an exposure time of 400 ns and a delay time of 8 μs to synchronize the framing with the discharge current pulse in each half voltage cycle. It can be clearly seen that there is a great similarity between any two adjacent patterns. By comparing the six pictures carefully, it is found that some spots ignite or vanish, and some locate at the same positions and shift with very small displacements in turn. However, the filamentary structure in each instantaneous pattern looks nothing like a spiral. For showing the movements of the spots more clearly, Figs. 5(b) and 5(e) are superposed and shown in Fig. 6, in which the directions of the spot movements are denoted by arrows. It is observed that some spots fix at the previous positions, and some ones in Fig. 5(e) locate closely to those in Fig. 5(b). It is also found that the moving spots randomly shift forward and backward along the spiral arms, and their location changes are less than the spots radii. In all, the spots have two possible spatiotemporal behaviors within continuous discharges: pinning at the same locations, and shifting along the arms with a small displacement. Therefore, it is the shifting movements that result in the filament footprints increasing and then form the arms of the spiral pattern over a long time. In another word, the continuous spiral arms, seen with naked eyes, can be considered as the integration of the trajectories of the spots randomly shifting over a long time. Furthermore, the statistics of the spots in a large number of the six-picture sequences shows that the six pictures in one sequence nearly have the same number of the spots, which means that the spots shown in each picture are all that the spiral pattern has during one discharge event. This, from another perspective, also illustrates that only if these discrete spots move and develop trajectories can the continuous smooth arms of the spiral patterns be available over a long time.

For quantifying the degree of similarity between successive patterns, a large number of the six-picture sequences of instantaneous patterns are used to calculate the cross correlations [20] between the first patterns and their subsequent patterns as a function of the delay time. The averaged correlation coefficients with an error of 0.15 and the exponential fitting curve are shown in Fig. 7. It can be drawn that the correlation time, the delay time when the correlation coefficient equals to $1/e \approx 0.37$, is about 16 μs, just equivalent to two half cycles of the applied voltage. Above $1/e$, the two pictures can be considered with relatively high similarity.

At present, the exact mechanism of the random movements of the filaments composing the spirals is not quite certain yet, but we may provide two possible explanations here.

In dielectric barrier discharge, the discharges ignited at the positions where more surface charges are deposited in the previous half cycle. Generally, it is believed that every discharge filament tends to stay at nearly the same place, which is called the memory effect of surface charges. Recently, a new discharge mechanism is introduced by B. Bernecker to explain the dynamical aspect of filaments in dielectric barrier discharge [21]. It is considered that the voltage drop produced by surface charges of discharge filaments can't completely inhibit the discharge formation between filaments. The discharge is generally invisible and called as a dark discharge, which belongs to the Townsend discharge. It can lead to the triggering of discharges at locations between the filaments of the previous half-cycle, and thus result in the motions of discharge filaments. Depending on above discussions, the movement states of filaments in the spirals are probably attributed to the memory effect combined with the dark discharge effect. Generally, filaments may keep relatively stationary when the memory effect plays a main role while they shift slightly when the dark discharge effect plays a main role.

From another perspective, the random movements of the filaments probably results from something like localized heating that changes some local discharge conditions. For instance, the temperature of the dielectric surfaces increases with continuous discharges. Wall charges of one filament should be given more energy by heating, and accordingly become more active and movable, eventually leading to the ignitions at different positions. By this, the filament movements can be considered as a certain kind of thermal disturbance caused by plasma heating.

IV. CONCLUSION

The formation of the spiral patterns in dielectric barrier discharge system is investigated through pictures with different exposures and the instantaneous pictures at successive driving half cycles taken by an ICCD camera. The spirals, like many other lattice patterns, are also found to be composed of filaments under the streamer mode. Generally, an individual filament has two possible movement states within continuous discharges: pinning at the same locations and shifting along the arm with a small displacement (less than the filament radius). It is the shifting movements that contribute to the formation of the spiral arms by increasing the length of the footprints (trajectories) over a long time. The averaged correlation time between the instantaneous patterns is found to be about 16 μs by cross correlation calculations. The dark discharge effect and the plasma heating effect are considered as the two possible explanations for the randomly forward and backward movements of the filaments.

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Figure Captions

FIG. 1. (Color online) Schematic representation of the discharge cell.

FIG. 2. (Color online) Spiral patterns appearing at a sustaining applied voltage in DBD in an air and argon mixture. The exposure time of the images is 40 ms. Experimental parameters: applied voltage U=4.2 kV, voltage frequency f=62.5 kHz, gas pressure p=380 Torr, discharge gap d=2 mm, air content χ=4%.

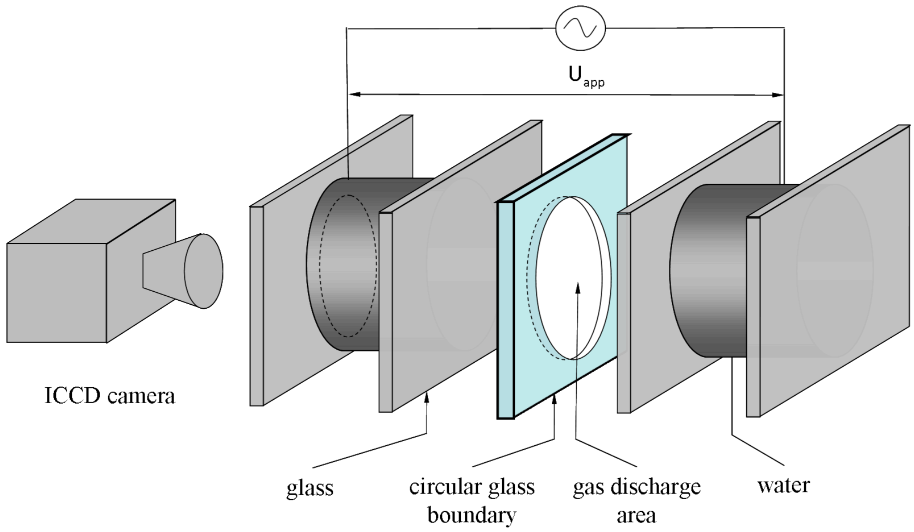
FIG. 3. (Color online) Waveforms of the applied voltage and the discharge current of the spiral patterns.

FIG. 4. Pictures of a spiral with different exposure times taken by three channels of an ICCD camera, which are triggered synchronously. The exposure times of the image (a), (b), and (c) is 200 μs, 48 μs, and 8 μs, respectively. Frequency of the applied voltage f=62.5 kHz.

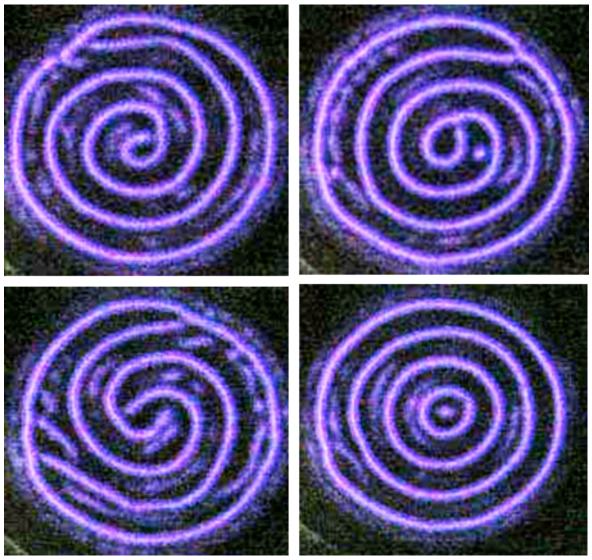
FIG. 5. Instantaneous images corresponding to six successive discharge pulses of the spiral. The exposure time of each image is 400 ns and the delay time between two adjacent images is 8 μs. Frequency of the applied voltage f=62.5 kHz.

FIG. 6. (Color online) Superposition of Fig. 5(b) and 5(e). Arrows denote the directions of movements of the filaments.

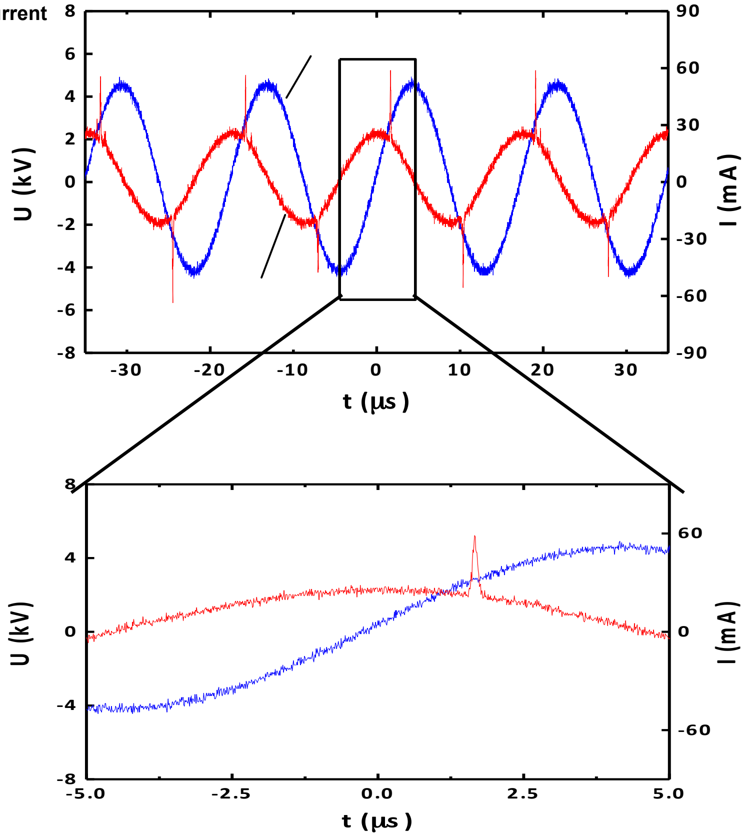
FIG. 7. (Color online) Cross correlation between two instantaneous images as a function of the delay time.

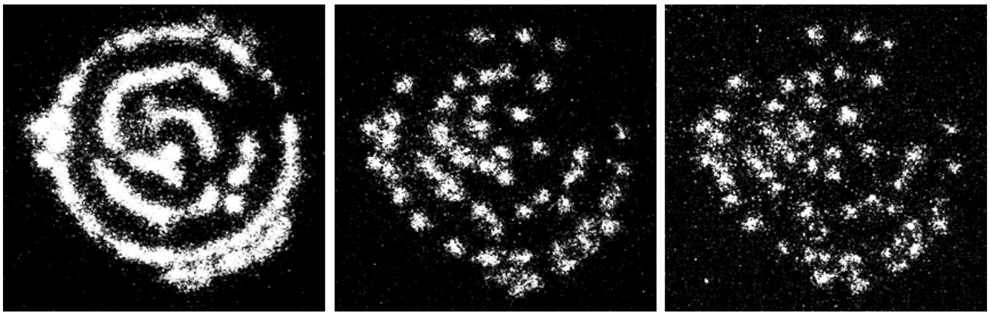


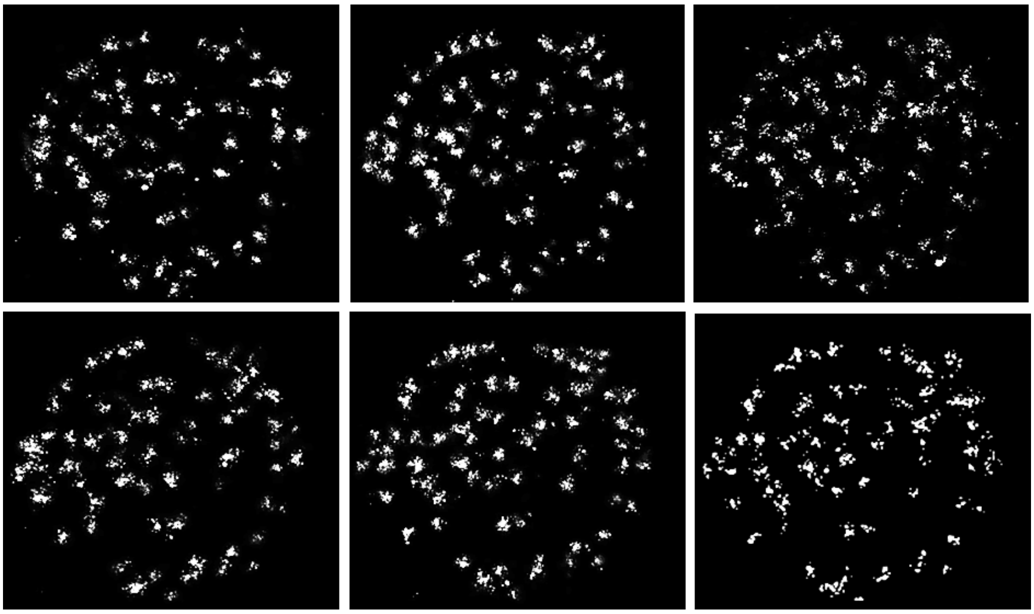
U_{app}
ICCD camera
glass
circular glass
boundary
gas discharge
area
water

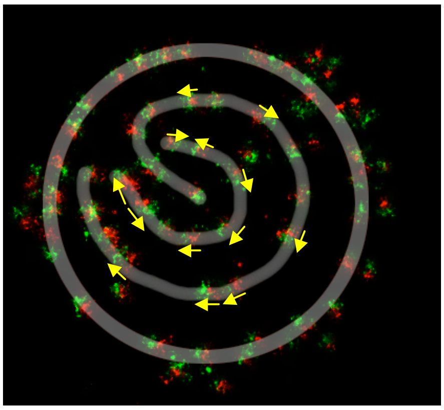


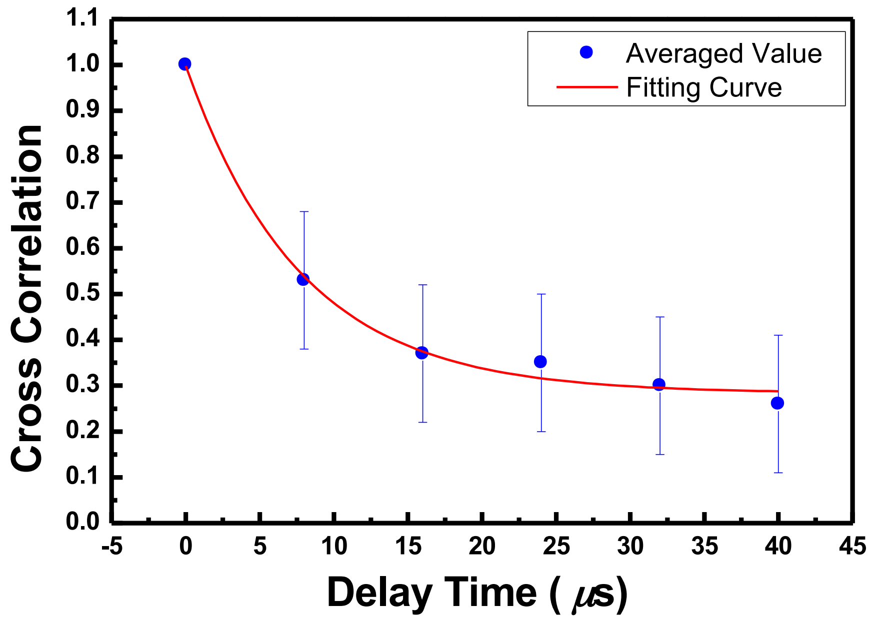
Voltage


Current
U (kV)
I (mA)
t (μs)
8
6
4
2
0
-2
-4
-6
-8
90
60
30
0
-30
-60
-90
-30
-20
-10
0
10
20
30
U (kV)
I (mA)
t (μs)
8
4
0
-4
-8
60
0
-60
-5.0
-2.5
0.0
2.5
5.0








Averaged Value
Fitting Curve
Cross Correlation
Delay Time (μs)
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0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-5
0
5
10
15
20
25
30
35
40
45