Formation of white-eye patterns with microdischarge in an air dielectric-barrier-discharge system

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We report on the observation of a white-eye pattern in an air dielectric barrier discharge. The patterned discharges undergo a development as follows: random spots–quasihexagonal pattern–hexagonal pattern (type I)–hexagonal pattern (type II)–white-eye pattern–chaos, as the voltage is increased. The spatiotemporal characteristics of the patterned discharges are investigated by using an optical method. Results show that the two discharge modes, uniform mode and filamentary mode, are actually two different spatial presentations of the same origin: the microdischarge. From the viewpoint of pattern dynamics, the white-eye pattern results from a three-wave resonance interaction.

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Dielectric barrier discharge (DBD, also referred to as silent discharge) is a type of nonequilibrium, nonthermal gas discharge, which has given rise to two subjects of great interest at present: i.e., investigation of pattern formation in DBD and realization of atmospheric-pressure glow discharge. It is characterized by a dielectric between electrodes and governed by electron avalanches ignited in the gap. Based on the evolution of an avalanche, DBD can exhibit two major modes: homogeneous or glow mode and filamentary mode [1,2]. In the homogeneous mode, numerous small avalanches develop under low field, avoiding streamer formation. The discharge shows a homogeneous feature across the electrodes and has only one current pulse per half cycle of the applied voltage [3]. There is also another type of discharge with a homogeneous appearance (referred to as streamer-coupling discharge) obtained under specific conditions, in which the preionization associated with a rapid increase of the voltage efficiently induces the simultaneous development of so many streamers that they interfere and develop as a single discharge channel covering a large area [1]. In the filamentary mode, a number of individual breakdown channels, which are referred to as microdischarges [3], occur due to the secondary avalanches and high internal field of primary avalanches. The filamentary mode is characterized by numerous microdischarges distributed in the discharge gap and by many current pulses per half cycle of voltage [3]. In fact, all the discharges in different modes are composed of plasma domains induced by the avalanches. Thus, the observed patterns in DBD must be related to these plasma domains. Boyers and Tiller reported that the hexagonal pattern, obtained in atmospheric-pressure helium, is an assembly of glow-discharge plasma domains [4]. In one review article, Kogelschatz showed that the two-dimensional (2D) discharge pattern obtained under certain conditions is presumably an arrangement of a number of smaller diffuse discharge areas [5]. Zanin *et al.* considered the discharge pattern as a regular arrangement of filaments through interaction with each other [6]. But there is still no direct experimental evidence indicating the composition of the discharge patterns.

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In this paper, we report on an experimental study of the patterned discharges in an air dielectric barrier discharge. A white-eye pattern is observed in DBD. The spatiotemporal characteristics of patterned discharges are investigated. It is found that the two discharge modes, uniform mode and filamentary mode, are actually two different spatial presentations of the same origin: the microdischarge.

The experimental device used in this work is similar to that described previously [7,8]. Two cylindrical containers, with inner diameter of 70 mm, sealed with 1.5-mm-thick glass plates, are filled with water. Here, the water acts as a liquid electrode. The parallel glass serves as the dielectric layers. A circular glass ring with diameter of 70 mm serving as a boundary limits the lateral diffusion of the discharge gas. The electrode system is situated inside a vacuum chamber filled with ambient air. The gas pressure is varied from 76 to 760 Torr, and the gas gap can be changed from 0.1 mm to 4 mm. The gas is refreshed when changing the gas pressure or the gas gap width. The temperature of water electrodes increases no more than 5 °C during an experiment (within about 10 min). Light emission of the discharge is detected by photomultiplier tubes (PMTs) (photoelectric multiple tube, RCA7265) and recorded with an oscilloscope (Tektronix TDS3054B). A charge-coupled-device (CCD) camera is used to record the images of discharge. The visible emission spectrum from the discharge is obtained through a monochromator (Acton Spectra Pro 2750, grating: 300 grooves/mm).

Figure 1 shows the development of patterns, random spots–quasihexagonal pattern–hexagonal pattern (type I)–hexagonal pattern (type II)–white-eye pattern–chaos, as the voltage was increased. All these patterns consist of spots and an illuminated background. It can be seen that the characteristics of the spots in Figs. 1(a)–1(c) are different from that in Figs. 1(d)–1(f). We refer to the spots with large area and low intensity in Figs. 1(a)–1(c) as type-I spots, and the spots with small area and high intensity in Figs. 1(d)–1(f) as type-II spots. In fact, there is a spontaneous jumping transition between the two types of spots with increasing voltage. The transition can happen to and fro when the voltage reaches 2.9 kV with other parameters fixed. The mean interparticle space could hardly change, and the system exhibits hexago-

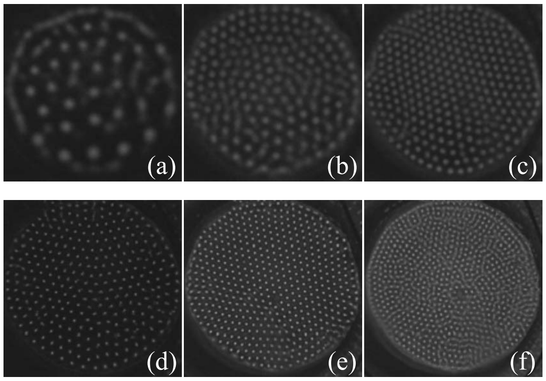

FIG. 1. Evolution of patterns with increasing voltage. (a) Random spots, 2.3 kV; (b) quasihexagonal pattern, 2.7 kV; (c) hexagonal pattern (type-I spot), 2.9 kV; (d) hexagonal pattern (type-II spot), 2.9 kV; (e) white-eye pattern, 3.4 kV; (f) chaos, 4.3 kV. The other control parameters: $p=0.12$ atm, $d=2$ mm, and $f=50$ kHz.

nal pattern, while the background is not intense enough to form the white-eye pattern. However, the luminance of the illuminant background increases with the voltage. When the voltage reaches about 3.2 kV, the background can be seen clearly. At this time, the background forms a honeycomb pattern surrounding a hexagonal lattice (type-II spots), and the white-eye pattern comes into being as shown in Fig. 2. So the white-eye pattern is composed of the hexagonal lattice of type-II spots and the intense background.

It has been seen that the background, type-I spots, and type-II spots have different spatial characteristics, but there is still no idea whether they belong to different discharge modes. Therefore, it is necessary to investigate their spatiotemporal characteristics for understanding the pattern formation. Here, we employ an optical method with PMTs to study the temporal and spatial characteristics of spots and background. The spots in Figs. 1(a) and 1(f) drift at a velocity of the order of mm/s, while they are nearly stable in Figs. 1(b)–1(e). So it is available to target and track certain spots with movable PMTs. For the temporal aspect, the time resolution can be realized at the ns scale, which is less than the duration of discharge in air. For the spatial aspect, the size of the spots in Fig. 1 is larger than 0.4 mm. We use a lens to image the pattern and a hole aperture to enable part of the light of discharge pattern, such as a partial spot, to enter the PMT. All measured areas of the pattern are of the order of

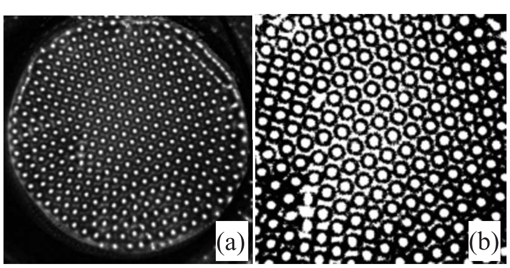

FIG. 2. White-eye pattern. (a) Original image. (b) Partial image after enhancing the contrast. The parameters are the same as those in Fig. 1(e).

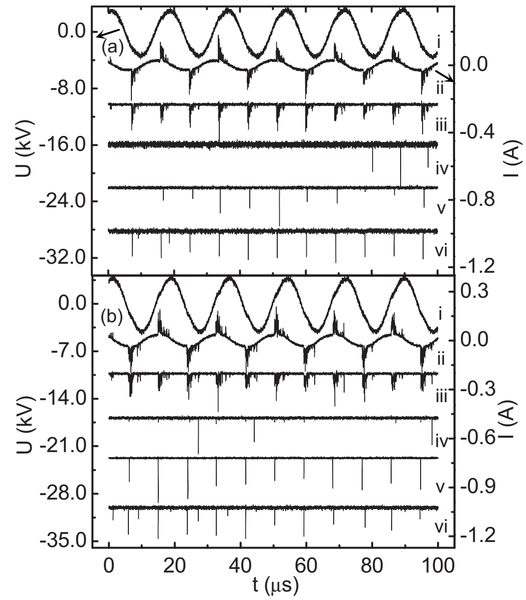

FIG. 3. Discharge wave forms (a), (b) of the hexagonal pattern [Fig. 1(c)] and white-eye pattern [Fig. 1(e)], respectively. The signals i–vi correspond to the applied voltage, current, total light emission, part of background, part of spot, and a whole spot together with partial background nearby, respectively. The measured area of pattern is of the order of 10^{-2} mm^{-2}, which is kept about 5% of that of one spot.

10^{-2} mm^{-2}, which is about 5% of area of one spot. So the spatial resolution can be realized at the micron scale. Therefore, this optical method is available for the high spatiotemporal resolved measurement of patterned discharge.

In the experiment, the signals of part of the background, part of the spot, and a whole spot together with partial background nearby are measured with increasing voltage. It is found that the background, type-I spots, and type-II spots have distinctive characteristics. Typical results are shown in Fig. 3, which corresponds to a hexagonal pattern [Fig. 1(c)] and the white-eye pattern [Fig. 1(e)]. For the partial background, the discharges under different voltages have similar signals with discontinuous and random current pulses in consecutive half cycles as can be seen in Figs. 3(a) (iv) and 3(b) (iv). This implies that there should be a certain microdischarge channel igniting randomly or moving through the measured area within several half cycles. So the observed uniform background is an integration of a large number of microdischarges and operates at uniform mode. For the type-I spots, when a partial spot is measured the discharge pulses are discontinuous in consecutive half cycles as shown in Fig. 3(a) (v). But when a whole spot together with partial background are measured simultaneously, the pulses occur at every half cycle as indicated in Fig. 3(a) (vi). So the type-I spot is also an integration of a large number of microdischarges and operates at uniform mode, which likes the case of background discharge. The microdischarges are restricted in a small area forming the type-I spot. Therefore the hexagonal pattern in Fig. 1(c) (type-I spots) actually is an arrangement of a number of smaller uniform discharge areas, which is in agreement with the opinions of Kogelschatz. For the type-II spots, not only partial spot within area of 10^{-2} mm^{-2} but also a whole spot do discharge at every half cycle as shown in Fig. 3(b) (v), (vi). Thus the type-II spots are filaments that present the microdischarges ignited on the same position in consecutive half cycles and operate at filamentary mode. The hexagonal lattice of white-eye pattern in Fig. 1(e) is composed of filaments (type-II spots). From the above results, we can draw a conclusion that the background and the type-I spots are an integration of a large number of microdischarges and operate as a uniform mode, while the type-II spots are actually filaments and operate as a filamentary mode. So the two modes are different spatial presentations of microdischarges.

Furthermore, the optical emission spectroscopy of the white-eye pattern is investigated. As Choi *et al.* stated, the relative intensity of the first negative band system of N_2^+ (391.4 nm) and atomic oxygen (777.1 nm) can be used as a criterion to determine the discharge mode [9]. In the present experiment, we obtain the relative intensity of the first negative band system of N_2^+ (391.4 nm) and N_2 (380.4 nm) after normalization of the second positive band system of N_2 (357.6 nm). The relative intensity of the background (type-II spots) is about 3.9 (3.6). In addition, by analyzing the vibrational temperature of the white-eye pattern from the second positive band system of N_2, it is found that the vibrational temperature of the background (type-II spots) is about 2787 K (2767 K). These results show that the relative intensities of $I_{N_2^+}/I_{N_2^*}$ and the vibrational temperatures of the background and the type-II spot are nearly equal, respectively. So we can come to the same conclusion as mentioned above.

As far as the above patterned discharge is concerned, two particular aspects have to be pointed out. On the one hand, the separation of spot and background in space gives rise to two current pulses humps at every half cycle. The first (second) one only contains the discharges of spots (background), which can be seen in Fig. 3. In general, once the voltage reaches a critical one, the spots discharge and can self-organize into patterns under proper control parameters. There exist some places between spots where the effective electric field is higher than that in the spot due to the action of surface charges. A continuous increasing of voltage on its rising edge can lead to the discharge of background among spots, which refers to as interpolative discharge. Furthermore, in the air discharge, oxygen is electronegative and it captures electrons and weakens the electron avalanche processes around the filaments. This reduces the diameter of filament and increases the ignition voltage of the gas around filaments, which leads to the dark ring round filaments (type-II spot) in the white-eye pattern. On the other hand, the transition between the two types of spots is a jumping process when the voltage reaches a critical value. The type-I spot oscillates within a large spatial scale, leading to uniform spatial presentations of the microdischarges. The interaction among spots is enhanced as the voltage is increased. Then the spots are further restricted close to their balance places, resulting in the formation of type-II spots when the voltage reaches a threshold value. More detailed experiments are needed in future work in order to explain this transition.

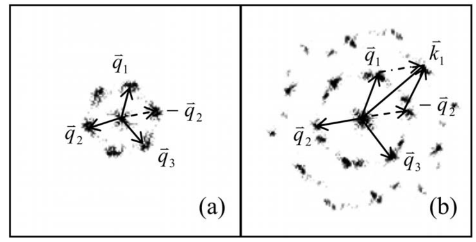

FIG. 4. Spatial spectra of hexagonal pattern (a) and white-eye pattern (b).

From the viewpoint of the dynamics of pattern formation, the white-eye pattern in the reaction-diffusion system has proved to be an interaction between two modes with different wavelengths [10]. To study the resonance of the white-eye pattern in Fig. 1, we analyzed the Fourier spectra of Figs. 1(c) and 1(e). As is well known, the hexagonal pattern satisfies a resonance condition $\bar{q}_1=-\bar{q}_3-\bar{q}_2$ as shown in Fig. 4(a). With increasing voltage, the background is intensified gradually and the white-eye pattern forms following the hexagonal pattern. Meanwhile, a mode (**k**) induced by the background is excited and interacts with the mode **q**. A new resonance relationship appears in the white-eye pattern, which satisfies $\bar{k}_1=\bar{q}_1-\bar{q}_2$ [Fig. 4(b)]. So the white-eye pattern in the DBD system results from a three-wave resonance.

In conclusion, two discharge modes, uniform and filamentary, are observed in patterned discharges in air. They are actually different spatial presentations of the same origin: microdischarge. The observed white-eye pattern consists of a honeycomb background and hexagonal lattice, which have proved to be operated at uniform and filamentary modes, respectively. From the viewpoint of pattern dynamics, the white-eye pattern results from a three-wave resonance interaction.

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