# Concentric-Ring Patterns in a Dielectric Barrier Discharge System

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We report on the first experimental observation of a concentric-ring pattern in a short planar dielectric barrier gas-discharge system and study its spatiotemporal behavior. While increasing the gas pressure the destabilization of the rings into a filamentary structure is observed. The charge carriers deposited on the dielectric electrodes determine the spatiotemporal behavior of the pattern.

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The investigation of self-organization and pattern formation processes [1,2] in laboratory conditions has been the subject of great interest in recent years. Propagating fronts, waves, solitary structures, spirals, and Turing patterns have been observed and studied. These structures are commonly observed in biological [3], chemical [4], and physical systems, such as hydrodynamical [5] and nonlinear optical [6] systems. An interesting class of pattern-forming systems is represented by spatially extended periodically driven systems, such as vibrated fluids (Faraday experiment) and granular media [2,7,8], and systems based on photosensitive chemical reactions under periodic illumination [9]. The dielectric barrier gas-discharge system investigated in the present work belongs to this class.

An important role for the pattern formation play symmetry constrictions imposed by the geometrical shape of the investigated system. In the case of a symmetric circular domain, a roll pattern in a Rayleigh-Bénard cell forms a concentric-roll pattern [2,10] consisting of a set of concentric rings. Such a pattern can be considered as a Turing pattern [11] on a circular domain or as a stationary roll pattern with a disclination defect imposed by the circular symmetry of the domain boundary [2]. According to [12], there is no experimental observation of stationary concentric rings in biological, chemical, and electrochemical systems. As a transient state concentric rings have also been observed in vertically oscillated fluids [13].

In this Letter we report on the experimental observation of a motionless targetlike form of a planar barrier gas discharge on a circular domain, which we denote, following [12], as a concentric-ring pattern. The visually observed structure occupies the entire discharge area, as shown in Fig. 1. Actually, this figure shows a time-averaged pattern having an interesting spatiotemporal substructure, which differs from the behavior of patterns in other periodically driven systems.

To our knowledge, this is the first observation of this pattern in the barrier gas-discharge system, where many other patterns were observed earlier. Among them are stripes and filaments [14], hexagonal filament arrangements, and focus defects emitting outwardly traveling circular waves [15], and other complex two-dimensional patterns [16,17]. We also observe distortion of the structure and transition to bright spots, which will be referred to as filaments. These filaments are localized spatial structures similar to those reported in [15,16].

The experimental system under consideration is schematically shown in Fig. 2. It includes a gas-discharge cell placed in a vacuum chamber, a high voltage ac power supply, and an image acquisition system connected to a PC. The discharge cell has a sandwichlike structure that comprises two thin plain-parallel glass plates separated by a thin gas layer. The glass plates are 1 and 0.7 mm thick. The gas layer formed by a spacer is $d = 2$ mm thick and 40 mm in diameter. The outer sides of the glass plates are coated with indium tin oxide (ITO) electrode layers, which are conductive and transparent to visible light. The system is driven by the sinusoidal ac voltage, whose frequency in the experiments is 50 kHz.

Different CCD cameras are used in the experiment. To get an overall view of the pattern formation process, a conventional video camera providing a frame rate of 25

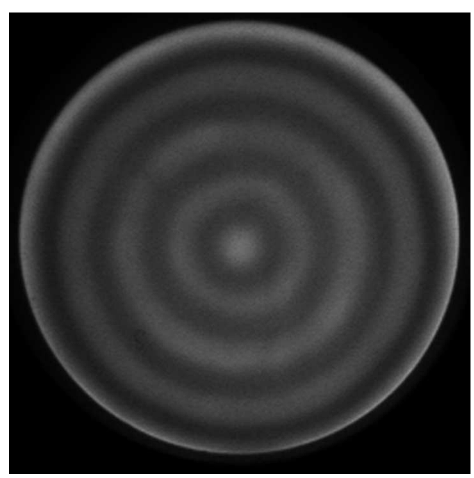

FIG. 1. Sample of the concentric-ring pattern observed in barrier gas discharge in nitrogen. Peak to peak value of supply voltage $U_{pp} = 1050$ V; gas pressure $p = 2.5$ hPa. The image was made by means of a video CCD camera with exposure time of 40 ms. Diameter of the gas-discharge area $D = 40$ mm.

  

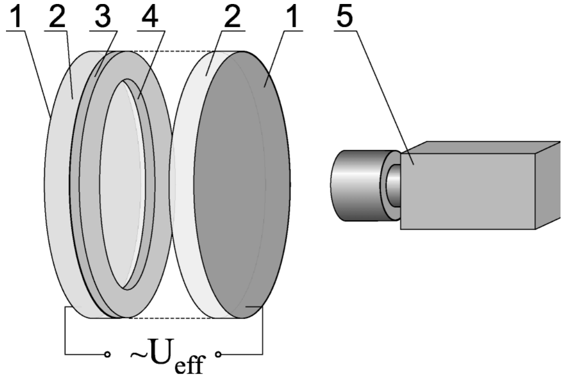


FIG. 2. Schematic representation of the discharge cell. The cell contains transparent ITO electrodes (1), deposited on glass plates (2), and spacer (3), which, together with glass plates (2), form the discharge area (4). Discharge is observed with a camera (5). The spacer contacts both glass plates. The front glass plate is shifted on the scheme to the right in order to show the discharge area.

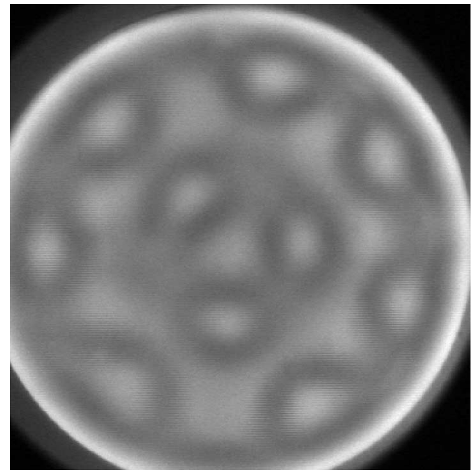

FIG. 3. Sample of the destabilized concentric-ring pattern observed in the barrier gas discharge in nitrogen. The peak to peak value of the supply voltage $U_{pp} = 1050$ V; discharge pressure $p = 4.0$ hPa. The image was made by means of a video CCD camera with exposure time of 40 ms.

frames per second (fps) and an exposure time of 40 ms is applied. In order to resolve the dynamics of a pattern, the fast intensified camera "Proxitronic 1000 FPS" that allows an exposure time down to 5 ns with frame rates up to 1000 fps and the intensified camera "DiCAM-2" are used. With the latter camera we could apply sampling of images and adding up the frames, thus increasing the signal/noise ratio of the resulting picture and revealing peculiarities in the dynamics of the pattern.

The current experiments are performed in nitrogen at a gas pressure ranging from 2.4 to 3.5 hPa, the corresponding values of $pd$ (product of the gas pressure and the distance between the electrodes) extend from 0.48 to 0.70 hPa cm. Such low values of $pd$ are not usual for pattern formation investigations in a dielectric barrier gas-discharge system; see e.g. [18]. The peculiarity of such low $pd$ values and low frequency of the supply voltage will be discussed below.

The discharge is ignited in a filamentary mode. An increase of the supply voltage causes the transition to the homogeneous state and leads further to the appearance of the concentric-ring pattern in the discharge luminance (Fig. 1). The structure is destroyed while increasing the gas pressure beyond the threshold of 3.5 hPa; see Fig. 3. The luminance distribution then looks similar to some of the flame patterns generated on a circular burner [19]. Further increase of the gas pressure causes the transformation to the filamentary mode. The filaments appearing after the destabilization of the concentric rings have the characteristic dimension close to the period of the concentric-ring pattern. We notice also that the transition from the ring structure to the filamentary discharge is accompanied by a change in the dynamics of the current: instead of double current peaks presented in Fig. 4 we observe then single current peaks.

The time series of the discharge current and the supply voltage corresponding to the concentric-ring mode are presented in Fig. 4. The observation of two narrow consecutive peaks in the discharge current for this mode means that the ignition of discharge takes place two times during one half period of the supply voltage. The phenomenon of a double discharge can be explained in frames of the model presented in [15] if one takes into account the charge accumulated on the dielectric plates forming the gas-discharge gap.

To prove that the observed structure is not formed by a set of rotating filament "necklaces" as in [14], the dynamics of the pattern has been analyzed with the fast Proxitronic 1000 FPS camera, although the destabilization of the rings to stationary spots (see Fig. 3) indicates

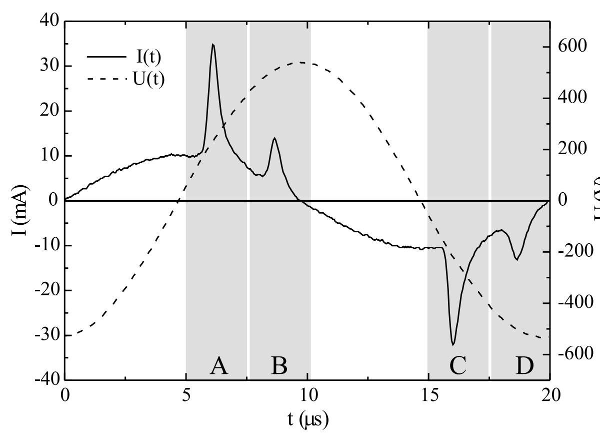


FIG. 4. Oscillogram of the discharge current $I$ (solid line) and the supply voltage $U$ (dashed line) corresponding to the concentric-ring pattern shown in Fig. 5.

this indirectly. The data obtained with the exposure time of 10 $\mu$s (one half period) show that the observed pattern is indeed a set of solid concentric rings and does not consist of running filaments, which could not be resolved with a conventional video camera. However, these data are too noisy to allow the detailed analysis of the patterns.

In order to obtain pictures with improved quality, the DiCAM-2 camera has been used. The signal-to-noise ratio has been increased by applying the sampling and integration technique. Finally in this way the images have been obtained by adding up 50 single frames, of which the exposure time is 2.5 $\mu$s and the repetition rate is 5 Hz. The acquisition events have been synchronized with a needed phase in current pulses by the external triggering of the camera. Figures 5(a)–5(d) show the luminance distributions corresponding to the first and to the second current peaks of the positive half period and of the negative half period of the supply voltage, respectively. The 2.5 $\mu$s exposure intervals are represented in Fig. 4 as gray stripes marked $A$, $B$, $C$, and $D$ corresponding to Figs. 5(a)–5(d), respectively.

As one can see in Fig. 5(a), during the first current pulse (the gray stripe $A$ in Fig. 4) the discharge forms two rings and a central spot. During the second current pulse (the gray stripe $B$ in Fig. 4) two rings are generated in the space that was free of discharge in the first pulse. The reason for the complementary form of the rings is related to the peculiarities of the electric charge transport: the charge deposited on the glass surfaces during the first current pulse reflects the pattern of the discharge and reduces the electric field in this area. In the area not affected by the first phase of the discharge the electric field is not diminished by the surface charge, consequently the second breakdown occurs there.

A video camera integrates the discharge luminance over a period of 40 ms, involving both discharge phases for hundreds of times. The result of this integration is presented in Fig. 1. Therefore this structure is a superposition of the patterns in Figs. 5(a)–5(d). The dynamics of the observed pattern differs from the commonly observed one for the periodically driven systems, where the response in the form of standing waves is subharmonic [2,9]. We point out that the harmonic response has also been experimentally observed and theoretically investigated for sufficiently thin fluid layers [20]. Here we observe another type of dynamics (see Fig. 5), which is a subject of further investigations.

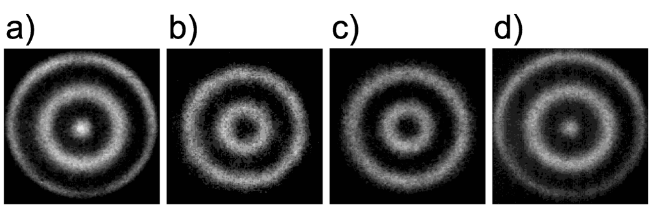


FIG. 5. Sequence of single discharge pulses of the concentric-ring pattern observed in the barrier gas discharge in nitrogen. Peak to peak value of the supply voltage $U_{pp} = 1050$ V, shown in Fig. 4; gas pressure $p = 2.5$ hPa. Images (a)–(d) represent patterns corresponding to the stripes A–D in Fig. 4, respectively. Each image is a sum over 50 frames made with the DiCAM-2 camera with exposure time of 2.5 $\mu$s.

Here we have reported the observation of a geometrically "perfect" concentric-ring pattern with an internal spatiotemporal dynamics in a low frequency ac dielectric barrier gas discharge and its destabilization into filaments. The duration of the observed discharge pulses is much longer than the electron and ion time of flight between the electrodes of the discharge cell. Thus, each current pulse represents a discharge similar to one in a dc case [21]. This allows us to attribute to some characteristics of dc gas discharge, such as the Paschen curve, to analyze its peculiarities.

We would like to stress that patterns studied in the present work are observed in a gas-discharge system operating on the left branch of the Paschen curve. Under these conditions the j-E characteristic of the gas is known to have no negative slope region [21,22], which plays a key role in some models of pattern formation in dc-driven gas-discharge systems [23]. We believe that our observations will give additional information for developing a physical model of pattern formation in dielectric barrier discharges. As one can see by considering the barrier discharge with a single breakdown during one half period of the supply voltage [15], such a system can be described in terms of an activator-inhibitor model [11,24]. The discharge current density, whose spatial distribution is visualized by the discharge luminance [25], produces charged particles in the volume of the gas. They are stored on the surfaces of the dielectrics and inhibit the discharge through their own electric field. The current activates not only the production of the inhibitor, but also of itself because of avalanche processes of charge multiplication in the discharge [21]. So, we can associate the discharge current with the activator and the transferred charge on the dielectrics with the inhibitor of an activator-inhibitor model. An alternative promising approach for description of patterns observed in ac-driven dielectric barrier gas discharge could be based on the continuum coupled map models [26].

The concentric rings observed in the presented experiments in the dielectric barrier gas-discharge system appear on a homogeneous discharge area. To prove the independence of the pattern on surface properties of the electrodes the experiment has been repeated with different glass plates and even with a crystal of semi-insulating GaAs, which has been used instead of one glass plate. In all these experiments the concentric-ring pattern displays the same properties. An increase of the gas pressure leads to the transformation to filaments through the angular destabilization of the concentric rings. The explanation of the destabilization mechanism as well as development of the activator-inhibitor model for the ac gas-discharge cell is an aim of a future research.

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