Study on Dynamic Behaviors of Ionization Waves Influenced by Feedback in a Glow Discharge Plasma*)

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Dynamic behaviors of ionization waves influenced by feedback are experimentally studied. Delayed feedback is useful for stabilization of chaotic system; it has applicability in controlling chaos. However, delayed feedback can also result in a stable system becoming unstable, or even chaotic. The ionization wave system in our experiment has one spatial degree of freedom. Neon gas is introduced into a glass tube that has been evacuated to high vacuum, and a glow discharge Ne plasma is produced by an electric current between two electrodes. Fluctuations in the light intensity are sampled using two photodiodes placed a certain distance apart; the intensity sampled from one photodiode is fed back to the system through an external circuit. The largest Lyapunov exponents are calculated from the time series sampled from the photodiodes. The value of the largest Lyapunov exponent is positive for chaotic oscillations, with higher values for more chaotic systems. The value becomes close to zero for a system with periodic oscillations. In our studies, we found that a chaotic system can be made periodic by applying feedback while the distance between two photodiodes is a multiple of a particular value.

Keywords: ionization wave, glow discharge, delayed feedback, chaos and periodicity, controlling chaos

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1. Introduction

From past decades up to present day, studies on control of disordered states such as chaos have been considered important [1–3]. In plasma science, controlling disordered states is important from the viewpoint of plasma application and controlled fusion, and several studies have been conducted [4–8]. The Ott, Grebogi and Yorke (OGY) [9] and time-delay auto-synchronization (TDAS) [10] methods of controlling chaos are widely used in many research fields [11–13]. In plasma physics, there are studies on control of chaotic behaviors involving stabilization of chaos observed in positive column under the glow discharge using OGY method [7] and in ion acoustic instability using TDAS method [8]. In particular, the TDAS method, which acts by the effect of delayed feedback, is robust against noise, and therefore it is applicable to noise-including experimental systems such as plasma. Here, we focus on dynamic behaviors of ionization waves [14, 15] in a glow discharge plasma. Ionization waves show various nonlinear behaviors, including chaos, as a function of the discharge current. Moreover, spatiotemporal behaviors can be observed using a simple detector such as photo diode. Therefore, ionization waves are a suitable experimental medium to investigate universal properties of nonlinear science. Dynamic behaviors of ionization waves have been well studied experimentally and theoretically [14–19]. Ionization waves exhibit a wide variety of nonlinear behaviors including chaos. In Ref. 5, it is discussed that feedback plays important role in the experiment about controlling chaos of ionization waves.

In this paper, we investigate dynamic behaviors of ionization waves influenced by feedback in a glow discharge. In Sec. 2, the experimental setup and configuration are described. In Sec. 3, results on dynamical behaviors of ionization waves influenced by feedback are discussed. In Sec. 4, the findings of this investigation are summarized.

2. Experimental Setup

The configuration of the experimental setup is shown in Fig. 1. All experiments are carried out using a glass tube with diameter and length of 0.02 m and 0.75 m, respectively. After evacuating the tube to a high vacuum, neon gas is introduced into the tube at a pressure of approximately 478 Pa. When a large DC electric field is applied to the electrodes, neon plasma is produced by glow discharge between the electrodes. The system shows various dynamic behaviors, including chaos, when varying the discharge current. The transformer incorporated in the circuit has a resistance of 8.0 kΩ. It works with a 9.4 kΩ resistor to sustain the glow discharge. Photodiode 1 is fixed, and photodiode 2 can move in the axial direction.

The ionization waves in these experiments are self-excited and unstable due to the plasma instability. The system has one spatial degree of freedom, as shown in Fig. 1. The phase velocity propagates from the anode to the cathode, i.e., the ionization waves travel from the left side to the

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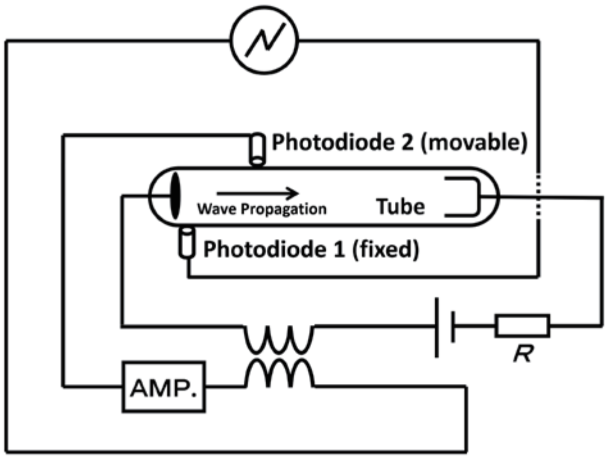

Fig. 1 Experimental schematic. The pressure in the tube is fixed at approximately 478 Pa, and the discharge current is varied. The time series signals are obtained from fluctuations in the light intensity using photodiodes. The signal sampled from photodiode 2 is amplified and added to the system.

right side of the discharge tube. The typical electron and ion temperatures are approximately 10 eV and 0.025 eV, respectively. The discharge current is varied to govern the system. The time series signals (waves) for the analysis are obtained as fluctuations in the light intensity using two photodiodes (S6775, HAMAMATSU) that are placed at a certain distance, and they are sampled using a digital oscilloscope (GDS-1072A-U, GWINSTEK). The signal sampled from photodiode 2 is used for feedback to the system through the external electric circuit. When the gas pressure is fixed at 478 Pa and the value of the discharge current is varied, the system exhibits a wide variety of oscillations, including periodicity and chaos [16]. Throughout these experiments, photodiode 1 is fixed slightly to the right of the anode. Only the signal sampled from photodiode 2 is used for feedback. The distance between two diodes matches up with distance from anode to photodiode 2. The signal sampled from photodiode 2 is amplified using an amplifier (4015, NF ELECTRONIC INSTRUMENTS) and added to the original system using a transformer (EF-4N, SHIMADZU) incorporated in the circuit as feedback. Since the ionization waves propagate from anode to cathode, i.e. travelling wave, there is some correlation between the signals obtained from photodiodes 1 and 2. This means that signals from photodiode 2 strongly relate to signals from photodiode 1, including a time delay that depends on the distance between the two photodiodes.

3. Results and Discussion

As described in the introduction, delayed feedback is often used for the control of the nonlinear system. Figures 2 and 3 show dynamic behaviors before and after applying feedback. Figures 2 (a), 2(b), and 2 (c) show the ionization wave's time series, power spectra, and the reconstructed trajectories embedded in phase space before applying feedback based on the method of [20] using time series date obtained as fluctuations in the light intensity using photodiode 1. The upper, middle, and lower traces show the time series, power spectra, and the reconstructed trajectories, respectively. Figures 3 (a), 3 (b), and 3 (c) show the time series, power spectra, and the reconstructed trajectories after applying feedback, as in Fig. 2.

In Figs. 2 (a) and 3 (a), the system shows chaotic oscillation without feedback, which changes to periodic oscillation upon applying feedback. That is, the system is stabilized and ordered by the feedback. Here, the discharge current is 25 mA, and the distance between photodiodes is 49 mm. In Figs. 2 (b) and 3 (b), the system shows chaotic oscillation without feedback and continues to show chaotic oscillation after applying feedback. That is, the system is not stabilized and not ordered by the feedback. Once again, the discharge current is 25 mA, but the distance between photodiodes is 30 mm. In Figs. 2 (c) and 3 (c), the system shows periodic oscillation without feedback, and then, it changes to chaotic oscillation after applying feedback. That is, the system is destabilized and disordered by the feedback. Here, the discharge current is 17 mA, and the distance between photodiodes is again 30 mm.

Feedback can introduce order, or it can destroy order. As can be seen by comparison of Fig. 2 and Fig. 3, the distance from anode to photodiodes 2 is the most important parameter to determine which effect applies. As described in Sec. 2, ionization waves propagate from the anode (left side) to the cathode (right side) in the discharge tube. Ionization waves have spatial wavelengths of several centimeters for the range of discharge current and pressure used to control this experiment [14]. Therefore, it is natural to think that there is a strong relationship between the wavelength of ionization waves and the changes in the system due to applying feedback. As can be seen by comparison of Fig. 2 (a) and Fig. 3 (a), a small peak (2.3 kHz) observed in Fig. 2 (a) increases and the system is controlled to periodic state with its frequency. To estimate the effect by applying feedback quantitatively, the largest Lyapunov exponents are calculated from the time series sampled from the photodiodes, based on the algorithm advocated in [21]. The value of the largest Lyapunov exponent is positive for chaotic oscillations; this value is higher for a more chaotic system. The value becomes close to zero for a system with periodic oscillations.

Figure 4 shows the change of system after applying feedback. The relationship between the distance between photodiodes and the largest Lyapunov exponent λmax is shown. Here, it should be noted that photodiode 1 is fixed and only photodiode 2 is moved, varying its distance from photodiode 1 as described in Sec. 2. Arrows in Fig. 4 indicate periodic states. λmax becomes smaller when the system shows periodic oscillation. λmax is calculated by adding together with two largest Lyapunov exponents cal-

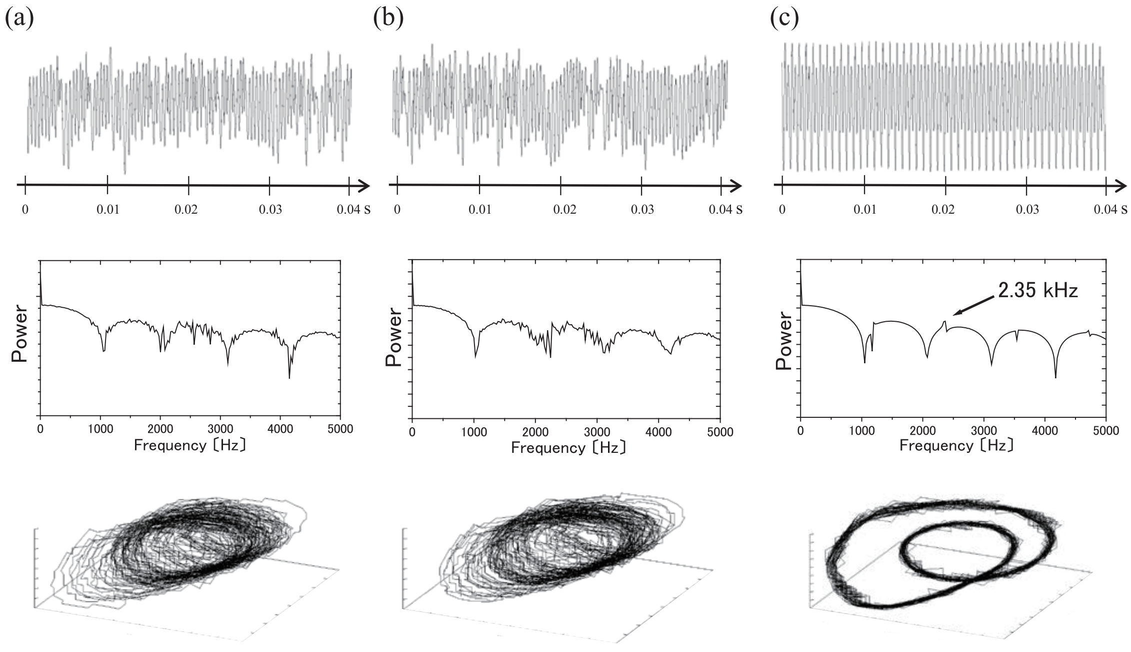

Fig. 2 Dynamic behaviors before applying feedback. Upper traces show the ionization wave's time series obtained from photodiode 1. Middle traces show the power spectra reconstructed from time series data obtained from photodiode 1. Lower traces show the reconstructed trajectories embedded in phase space using time series data obtained from photodiode 1. The value of the discharge current and the distance between photodiodes are (a) 25 mA and 49 mm; (b) 25 mA and 30 mm; (c) 17 mA and 30 mm.

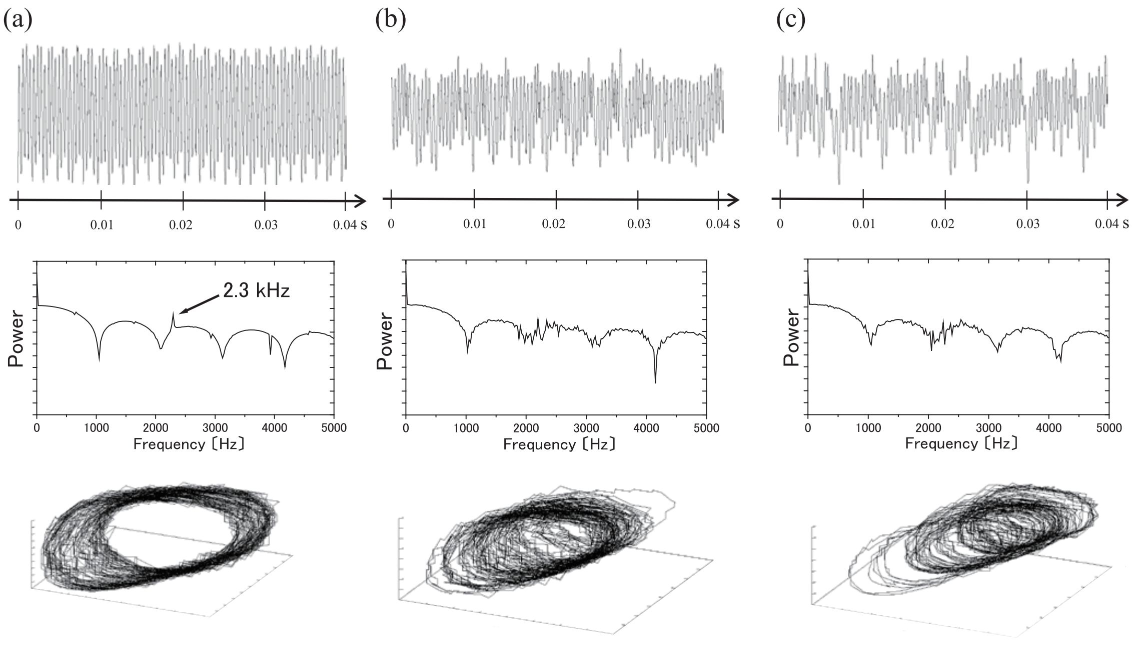

Fig. 3 Dynamic behaviors after applying feedback. Upper traces show the ionization wave's time series obtained from photodiode 1. Middle traces show the power spectra reconstructed from time series data obtained from photodiode 1. Lower traces show the reconstructed trajectories embedded in phase space using time series date obtained from photodiode 1. The value of discharge current and the distance between photodiodes are (a) 25 mA and 49 mm; (b) 25 mA and 30 mm; (c) 17 mA and 30 mm.

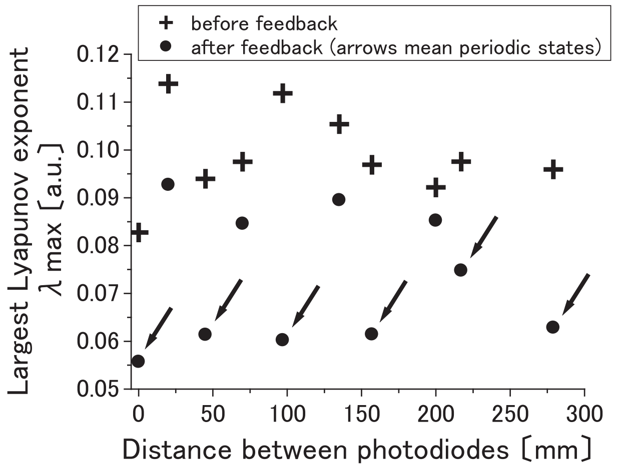

Fig. 4 The change to Lyaponov exponent λmax from applying feedback. The relationship between the distance between two photodiodes and λmax is shown.

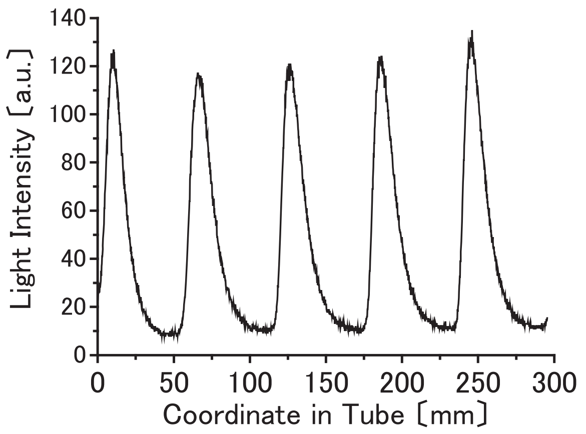

Fig. 5 Ionization wave spatial structure at a fixed moment in time when the discharge current is 25 mA, observed using a line-scan camera.

culated using time series signals obtained from photodiode 1 (waves) and photodiode 2 (feedback). From Fig. 4, we see that the system can change to periodic state at a regular photodiode spacing interval of roughly 50 mm. Figure 5 shows ionization wave spatial structure at a fixed moment in time when the discharge current is 25 mA, observed using a line-scan camera (TL-4096ACL, TAKENAKA). By comparing Figs. 4 and 5, we find that the spacing interval shown in Fig. 4 is closely linked to the wavelength of ionization waves.

4. Conclusions

Our findings concerning dynamic behavior of ionization waves influenced by feedback in a glow discharge are summarized as follows.

- When feedback is applied to the spatially extended system, it can increase or decrease the order in the system depending on the relationship between the original signal and feedback signal.
- A chaotic system can be made periodic by applying feedback from signals measured at a specific spatial interval, and the specific interval is closely linked to the spatial wavelength of ionization waves in a glow discharge.

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