Spontaneous transition of one-dimensional plasma photonic crystal's orientation in a dielectric barrier discharge*

Fan Wei-Li(范伟丽)† and Dong Li-Fang(董丽芳)

College of Physics Science & Technology, Hebei University, Baoding 071002, *China*

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A novel one-dimensional plasma photonic crystal whose crystal orientation can change spontaneously is demonstrated using a dielectric barrier discharge with two liquid electrodes. The orientation of the plasma photonic crystal will vary from transverse to longitudinal or vary from longitudinal to transverse and then revert to longitudinal by self-adjustment, while the experimental conditions are kept fixed. The dispersion relation of these plasma photonic crystals are calculated, and the changes of the photonic band diagrams during the orientation transition are studied.

Keywords: plasma photonic crystal, dielectric barrier discharge, orientation transition, photonic band diagram

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1. Introduction

Photonic crystal (PC) is a well known material used to control and manipulate the propagation of light.[1,2] This active research area has now been extended to the plasma photonic crystal (PPC) due to the material's tunable spatio-temporal properties.[3–21] The plasma photonic crystal is either a periodic structure of the plasma and dielectric material or a spatially periodic arrangement of the plasma density. In addition to the general characteristics of the conventional photonic crystals, such as bandgaps and negative refraction, the plasma photonic crystal has two unique features: strong dispersion around the electron plasma frequency and dynamic (time-varying) controllability.[14–16,19,20] The parameters of a plasma photonic crystal, such as the dielectric constant, the lattice constant, the filling ratio, the symmetry of the structure, the discharge moment and so on, can be controlled both spatially and temporally by tuning the individual plasma ignition or adding a changeable magnetic field, leading to a variation of the photonic band diagrams. Based on these properties, plasma photonic crystals can be widely used in plasma lenses, plasma antennas, plasma stealth aircrafts, etc to control the electromagnetic (EM) waves in the GHz to THz range dynamically.

As it is simple and representative, the one-dimensional (1D) plasma photonic crystal has gained much attention in recent years. Extensive theoretical studies have been carried out.[3–11] Hojo and Mase presented the concept of the PPC and discussed the dispersion relation of EM waves propagating in the PPC.[3] Shiveshwari and Mahto studied the transmission properties of PPCs,[4] while Qi *et al.* discussed the dependence of the dispersion relation on the external magnetic field.[7,8] Sheng *et al.* predicted the formation of plasma Bragg grating (i.e., plasma photonic crystal) by using two intersecting laser pulses at intensities of 10^{15} W/cm^2, and studied the dispersion relation and the optical properties of the plasma Bragg gratings by using both analytical methods and particle-in-cell simulations.[9–11] Experimental studies of plasma photonic crystals are relatively few, however, because of the limitations of experimental methods. Discharges with an artificial array of electrodes are generally used to generate PPCs, and both 1D and 2D plasma photonic crystals have been obtained. Sakai *et al.* and Faith *et al.* have done much work on this area and obtained the plasma photonic crystals for microwaves of millimeter wavelength ranges.[12–16]

In this paper, a novel one-dimensional plasma photonic crystal whose crystal orientation can change spontaneously is presented in a dielectric barrier discharge system. Rather than an artificial array of electrodes, two plate water electrodes are utilized, and the plasma photonic crystals are obtained by the self-organization of the discharge filaments. The orientation of the plasma photonic crystal can change spontaneously from transverse to longitudinal or from longitudinal to transverse then revert to longitudinal by self-adjustment when the experimental conditions are kept fixed. The dispersion relation of these plasma photonic crystals is calculated, and the changes shown in the photonic band diagrams during the orientation transition are discussed. A new type of one-dimensional plasma photonic crystal that can make a flexible and self-adjusting transition is suggested. The nonlinear instability and the boundary conditions are believed to be the two main factors giving rise to this phenomenon.

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†Corresponding author. E-mail: fanweili@hbu.edu.cn

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2. Experimental set-up

The experimental device is shown in Fig. 1. Two cylindrical containers are filled with tap water. A metallic ring is immersed in each of the containers and connected to a power supply. Thus, the water serves as a liquid electrode. The glass plates serve as the dielectric layers. As the lateral boundary, a rectangular glass frame whose area and aspect ratio can be varied freely is placed between two parallel glass plates to keep the plasma photonic crystals stable. A sinusoidal alternating-current (ac) voltage is applied to the electrodes. The power supply has a maximum peak voltage of 30 kV and a frequency range of 1–100 kHz. All of the apparatuses are enclosed in a big container filled with argon. The gas pressure can be varied from 0.10×10^5 Pa to 1.01×10^5 Pa. The amplitude of the applied voltage is measured by a high-voltage (HV) probe (Tektronix P6015A 1000X). A charge-coupled-device camera (Canon Powershot G1) is placed at one end of the electrode to record the image of the plasma photonic crystal.

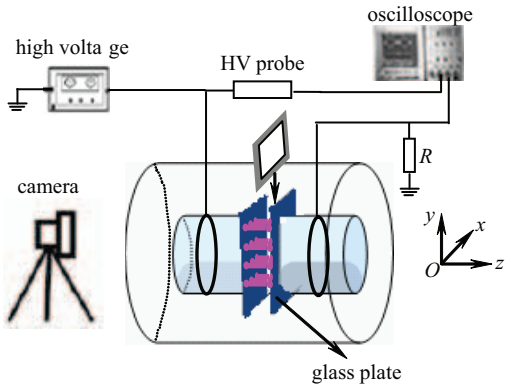


Fig. 1. (color online) Schematic diagram of the experimental setup.

3. Theoretical model and formulations

The dispersion relation of the EM waves propagating in the plasma photonic crystal is calculated by solving the Helmholtz equation. Details of the calculation methods have been described clearly in Refs. [9]–[11], so here we just give brief definitions of the parameters that will be used. In each period of the PPC (see Fig. 2), the dielectric constants of the plasma layer with thickness Ld and background material layer with thickness L are $\varepsilon_{\rm p}$ and $\varepsilon_{\rm m}$, respectively, and the ratio of the two thicknesses is d. Here $\varepsilon_{\rm p} = 1 - (\omega_{\rm pe}/\omega)^2/[1 - {\rm i}(\nu_{\rm m}/\omega)]$, where $\omega_{\rm pe}$ is the electron plasma frequency with $\omega_{\rm pe} = \sqrt{n_{\rm e}e^2/\varepsilon_0 m_{\rm e}}$, $\nu_{\rm m}$ is the electron elastic collision frequency determined by the neutral gas pressure and the elastic collision cross section.[22] The lattice constant of the plasma photonic crystal is defined as $\Lambda = (1+d)L$, which refers to the constant distance between the two units. Thus, the one-dimensional plasma photonic crystal is an alternating of two different dielectric constants ($\varepsilon_{\rm m}$ and $\varepsilon_{\rm p}$).

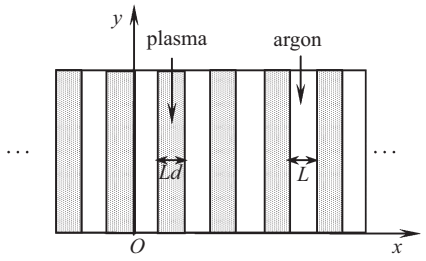


Fig. 2. Diagrammatic sketch of the 1D plasma photonic crystal for numerical analysis.

4. Experimental results and discussion

When the applied voltage is increased to the threshold, a breakdown occurs in the gas gap, and many discharge filaments are ignited. These filaments (plasma columns) can self-organize into different periodic structures[23,24] depending on the experimental parameters such as applied voltage, frequency, gas pressure, and so on. Increasing the applied voltage to an appropriate value, diverse 1D plasma photonic crystals are spontaneously formed, as shown in Fig. 3. The bright lines denote the plasma zones where discharges occur, while the black region represents the argon area where there are no discharges and the plasma is very thin. The dielectric constant of argon $\varepsilon_{\rm m}$ is approximately unity. As shown in Fig. 3(a), the plasma photonic crystal has a transverse direction, the plasma lines are horizontal. Although the experimental conditions are kept fixed, the crystal orientation begins to change from the left boundary (Fig. 3(b)). Once the transition starts, the original horizontal lines split up into a number of discrete spots, and the change of the crystal orientation occurs as these discharge spots re-link in the longitudinal direction, as shown in Fig. 3(c). As more spots re-link in the longitudinal direction, the area with an altered orientation expands.

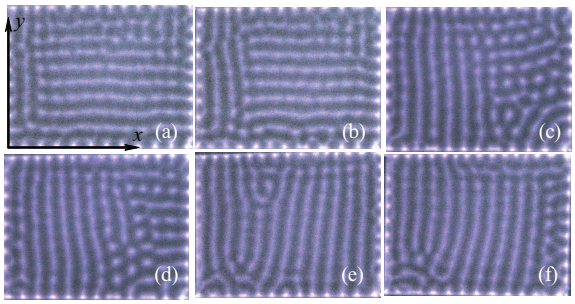


Fig. 3. (color online) One-dimensional plasma photonic crystals whose crystal orientation changes spontaneously from transverse to longitudinal. (a) Transverse plasma photonic crystal; (b)–(d) process of the spontaneous orientation adjustment of the plasma photonic crystals when keeping the discharge conditions fixed; (e) longitudinal plasma photonic crystal. Here $U = 6.4$ kV, $f = 55$ kHz, the size of the discharge boundary is 26 mm × 33 mm.

These discrete spots disappear and lines form again when the orientation has totally changed, as shown in Fig. 3(e). After a

self-adjustment, a well-ordered periodic plasma photonic crystal is generated (see Fig. 3(f)). The aforementioned evolution always takes several minutes, during which the experimental conditions are kept constant and the orientation transition of the plasma photonic crystal occurs spontaneously. If the incident electromagnetic wave is fixed, the orientation variation in the plasma photonic crystal is equivalent to a change of the incident angle of the electromagnetic wave. Thus, a new type of plasma photonic crystal is suggested here.

To clarify the impacts of the orientation transition on the propagation of EM waves, the changes of the structural parameters and the dispersion relation of the plasma photonic crystals are studied. Figure 4 shows the light intensity distributions of the plasma zones in different plasma photonic crystals and their corresponding band diagrams. It is found that both the structural parameters and the band diagrams of the plasma photonic crystals are slightly changed when the direction varies from transverse to longitudinal. For the transverse plasma photonic crystal (TPPC), the thickness of the argon layer is $L = 1.62$ mm, the length ratio of the plasma layer to the argon layer is $d = 0.73$, and the lattice constant is $\Lambda = 2.74$ mm. Note the value of d is calculated as follows. We first portray the spatial distribution of the light intensity of the PPC (the top row of Fig. 4). Then we define the line located at half amplitude as a reference, beyond which is the plasma region and below which is the argon region. The values of d and Λ are statistical results obtained by measuring the lengths of these two regions. For the longitudinal plasma photonic crystal (LPPC), $L = 1.61$ mm, $d = 0.64$, $\Lambda = 2.64$ mm. The lattice constants Λ and L change little, but the ratio d is greatly decreased. This is reasonable because when the orientation changes, the crystal periodicity increases, resulting from the limitations of the standing wave conditions and the boundary conditions. Consequently, both the proportion of the plasma with dielectric in one unit (the ratio d) and the light intensity of the plasma area will reduce (as shown in Figs. 3(f) and 4(b-1)), as the experimental conditions are fixed during the orientation transition, i.e., the input power is constant. Furthermore, we can also see the dispersion relation of the plasma photonic crystals with different orientations in Fig. 4. The results show that above the electron plasma frequency ($\omega_{pe}/2\pi$), plasma arrays produce the frequency regions of forbidden propagation and a series of pass bands with a certain phase velocity, just like the band structure in a conventional photonic crystal. However, multiple flatbands are formed when the frequency is below $\omega_{pe}/2\pi$ so that the plasma photonic crystal becomes a wave-propagating medium, while waves are usually forbidden to propagate in this range due to a cutoff phenomenon in the bulk plasma (the

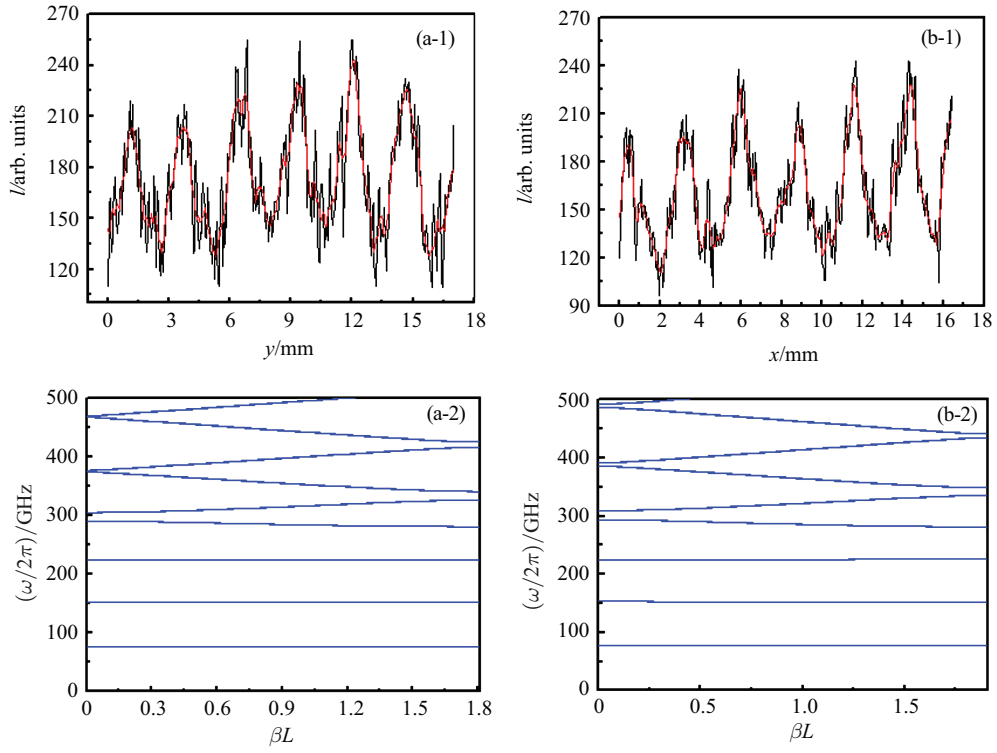


Fig. 4. (color online) Light intensity distributions of one-dimensional plasma photonic crystals of different orientations and their corresponding photonic band diagrams. Panels (a-1) and (a-2) respectively denote the light intensity distribution and the band structure of the transverse plasma photonic crystal shown in Fig. 3(a). The parameters are $L = 1.62$ mm, $d = 0.73$, $\Lambda = 2.74$ mm, $n_e = 10^{21}$ m^{-3}. Panels (b-1) and (b-2) respectively denote light intensity distribution and the corresponding band structure of longitudinal plasma photonic crystal shown in Fig. 3(f). The parameters are $L = 1.61$ mm, $d = 0.64$, $\Lambda = 2.64$ mm, $n_e = 10^{21}$ m^{-3}. Here β is the propagation constant for the structure as a whole.

electron plasma frequency is about 283 GHz, and the electron density n_e is in the order of 10^{21} m^{-3} which is measured using the spectral line profile method reported before[25]). As reported in Ref. [26], localized surface modes contribute to wave propagation along the flatband in a similar manner to localized surface plasmon in metallic photonic crystals. From these band structures, we can clearly see that the bandgap position shifts upward and the phase velocity is increased when the TPPC is changed to LPPC. The band frequencies ($\omega/2\pi$) of these PPCs are in the order of 10^2 GHz, so they can be used for the dynamic control of the propagation of the EM waves in this range. Sakai *et al.* have verified the plasma photonic crystal for microwaves in the millimeter wavelength range by using a millimeter wave detection device.[14–16]

Another type of spontaneous orientation transition is also observed, i.e., a sequence from longitudinal to transverse and then back to longitudinal, as shown in Fig. 5. Instead of the rectangular boundary used in Fig. 3, a square discharge boundary is utilized here, and the experimental conditions are also kept fixed. At the beginning, the crystal orientation is longitudinal (Fig. 5(a)). This periodic structure will be broken after a maintenance of several minutes and the lines will split into discrete spots. As these spots re-link in another direction, the crystal orientation changes (as shown in Fig. 5(3)), much the same as the behavior described in Fig. 3. After sustaining this for dozens of minutes, the TPPC begins to change direction from the right side of the boundary (see Fig. 5(f)), and finally returns to the LPPC via a gradual extending of the area with the changed direction (see Fig. 5(h)). It is worth pointing out that the periodicity can be seen to have reduced by one when comparing Fig. 5(h) with Fig. 5(a) although they have the same crystal direction. The periodicity change is attributed to the inevitable drift of device parameters because of the long duration of the experiment.

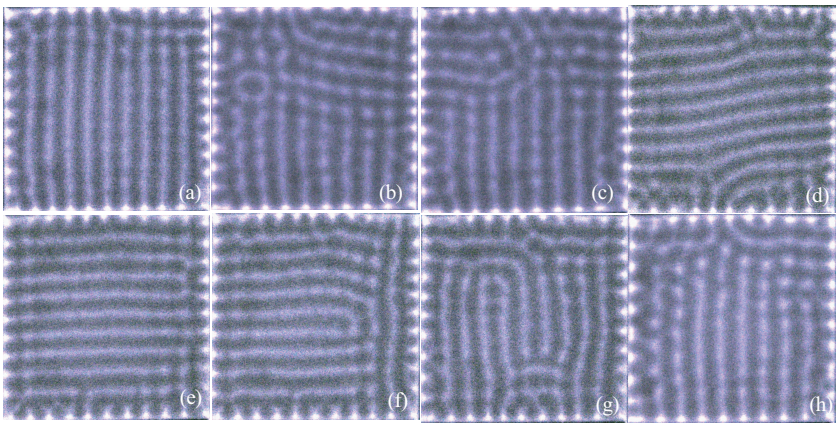


Fig. 5. (color online) One-dimensional plasma photonic crystal whose crystal orientation changes spontaneously from longitudinal to transverse then again to longitudinal. (a) Longitudinal plasma photonic crystal; (b)–(d) process of the spontaneous orientation adjustment of plasma photonic crystals when keeping the discharge conditions fixed; (e) transverse plasma photonic crystal; (f)–(g) process of the spontaneous orientation adjustment of plasma photonic crystals from transverse to longitudinal again when keeping the discharge conditions fixed; (h) longitudinal plasma photonic crystal. Here $U = 7.3$ kV, $f = 55$ kHz, the size of the discharge boundary is 24.5 mm $\times$ 24.5 mm.

Figure 6 shows the Fourier spectral analyses of the plasma photonic crystals during the transition, from which we can see the periodicity and the process of changing orientation clearly. It can be seen that when the plasma photonic crystal has a certain direction, only one pair of clear points emerge, as shown in Figs. 6(a), 6(d), 6(e), 6(g), and 6(h), which represent the periodicity of the plasma layers. But for the process of changing orientation, two pairs of points appear, indicating the coexistence of two directions.

The changes of the structural parameters as well as the band diagrams of the plasma photonic crystals during the transition are studied, as shown in Fig. 7. It can be found that the lattice constant remains constant when the original LPPC (Fig. 5(a)) evolves into the TPPC (Fig. 5(e)), and the ratio d as well as the length of the dielectric layer L changes very little, because the discharge boundary is square. Accordingly, the band diagrams are nearly unchanged in this process. However, for the next transition from TPPC to LPPC, the lattice constant is increased and the ratio d is decreased because of the inevitable drift of device parameters during the lengthy experiment. The bandgap widths are reduced and the bandgap positions shift downward correspondingly. Therefore, a novel plasma photonic crystal is presented here, whose crystal orientation can change spontaneously from longitudinal to transverse and then back to longitudinal. The band diagrams of the plasma photonic crystals are altered during the transition, indicating that a flexible control of light propagation is possible.

It should be pointed out that the aforementioned orientation transition phenomenon for 1D PPC occurs spontaneously when the discharge parameters are fixed. Generally, the ap-

plied voltage is the main parameter which greatly affects the spatial periodicity and the electron density of the PPC. With an increase of the applied voltage, the lattice constant of the PPC will be reduced by an order of 10^{-1} m or even more, while the size of the plasma layer will be greatly enlarged, leading to an increase of the proportion (d) of plasma to the gas. The changes of d are generally in the range of 0.6–1.8, and the electron density increases in a range of 10^{14}–10^{17} cm^{-3}. The variations of these plasma parameters will change the photonic band diagrams, as was studied in our previous work,[19,20] so we can control the light propagation of different frequencies effectively by just changing the applied voltage.

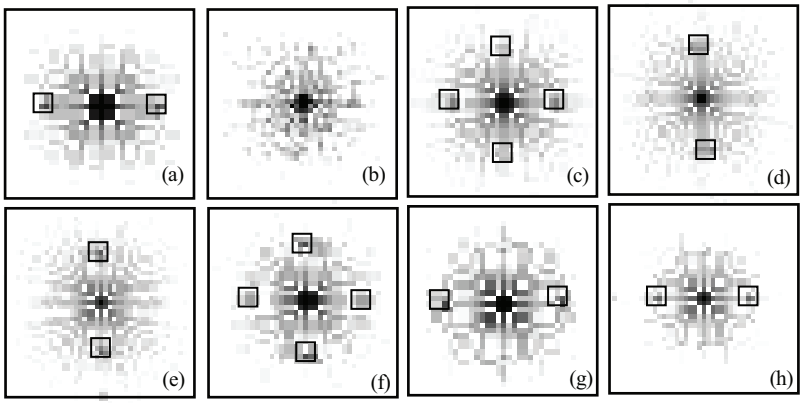


Fig. 6. The corresponding spatial Fourier spectra of the plasma photonic crystals in the orientation transition shown in Fig. 5. The periodicity of the plasma photonic crystal is indicated with black squares.

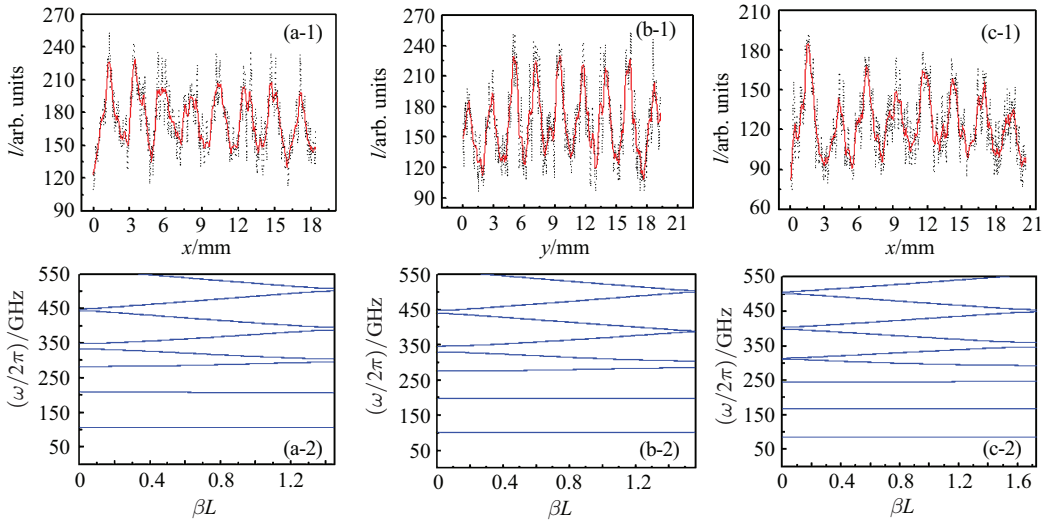


Fig. 7. (color online) Light intensity distributions of one-dimensional plasma photonic crystals of different orientations and their corresponding photonic band diagrams. Panels (a-1) and (a-2) respectively denote the light intensity distribution and the corresponding band structure of the longitudinal plasma photonic crystal shown in Fig. 5(a). The parameters are $L = 1.06$ mm, $d = 1.16$, $\Lambda = 2.3$ mm. Panels (b-1) and (b-2) respectively are the light intensity distribution and the corresponding band structure of the transverse plasma photonic crystal shown in Fig. 5(e). The parameters are $L = 1.14$ mm, $d = 1.01$, $\Lambda = 2.3$ mm. Panel (c-1) and (c-2) respectively are the light intensity distribution and the corresponding band structure of the longitudinal plasma photonic crystal shown in Fig. 5(h). The parameters are $L = 1.42$ mm, $d = 0.82$, $\Lambda = 2.58$ mm.

It is believed that two main factors are responsible for the phenomenon of spontaneous orientation transition. One is that our system is highly nonlinear, and the nonlinear instability plays an important role in the pattern selection. The other is the limitation of the boundary conditions. Once a random fluctuation emerges in the system, the system will magnify it nonlinearly, and the nonlinear instability will make the self-organized structures prone to decay or evolve into other patterns. On the other hand, stable string structures can be produced only when the standing wave condition is satisfied. The nonlinear modes of the two directions (transverse and longitudinal) both exist in the system (see Figs. 6(c) and 6(f)). Therefore, once the fluctuation emerges, the string patterns become instable and tend toward a new stable state. For a certain direction, if the boundary condition is just matched with the lattice constant of the string structure, i.e., the standing wave

condition is satisfied, the modes in that direction will play the dominant role and suppress the modes of the other directions. Sustaining this for a while, if another fluctuation emerges, the string patterns become unstable again and try a new selection under the influence of both nonlinear instability and the boundary conditions, which may result in the next orientation transition. We plan further study of the physical mechanism of this phenomenon and means of controlling the orientation transition.

5. Conclusion

A new kind of one-dimensional plasma photonic crystal whose crystal orientation can change spontaneously is demonstrated by using a dielectric barrier discharge with two liquid electrodes. The crystal orientation of the plasma photonic crystal can vary from transverse to longitudinal or from longitudinal to transverse and then back to longitudinal by self-adjustment while the experimental conditions remain fixed. This transition is equivalent to a change of the incident angle of an electromagnetic wave. The changes of photonic band diagrams of these plasma photonic crystals are studied, which reveals that both the bandgap widths and the bandgap positions will vary with the orientation transition. A novel one-dimensional plasma photonic crystal is suggested, whose behavior may lead to wide applications in many scientific and technical areas.

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