Annular Slot Antenna Large Area Microwave Planar Plasma Source

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Abstract

This article presents a design of the large area (312-mm-diameter) microwave planar plasma source. The source is powered by 2.45 GHz microwaves and its operation is based on the absorption of the energy of an electromagnetic wave propagating along the plasma-dielectric interface. The power is coupled to plasma through the dielectric plate by an annular slot antenna of the azimuthally symmetrical microwave applicator, which enables the production of the azimuthally symmetrical discharges on large diameters. The plasma source exhibits the resonant behavior with a discrete set of plasma densities bound to the particular electromagnetic modes sustaining the discharge. In argon, within the pressure range from 1 mTorr to 200 mTorr and within the power range from 200 up to 3000 W, plasma densities in the orders of 10^{11} - 10^{12} cm^{-3} and the electron temperatures from 1.2 to 3.8 eV have been measured. A special tuning system, which enables to achieve the complete matching, smooth plasma density change, control of the radial plasma density profile and plasma diameter is also presented. The effect of this tuning system on the discharge behavior and parameters are briefly discussed.

1. Introduction

The recent trend in the semiconductor industry worldwide has brought the demand for the large-area (≧10-inch diam.) high-density ($\geqq 10^{11}$ cm^{-3}) plasma sources for the thin-film-based plasma processing. Many researchers, especially in Japan, have turned their attention to the investigation of the microwave and UHF discharges produced on large diameters without the use of the static magnetic fields. As a result of this effort, recently and in the past, several large-area microwave [1-4] and UHF [5] plasma sources or plasma applicators [6,7] have been developed. Special category of these sources is formed by, as assigned in the literature, large area surface wave (sw) plasma sources. All of the large area sw-plasma sources reported up to now are of the family of microwave sources operating at the frequency of 2.45 GHz and their another common feature is that they use the open dielectric or air-filled resonator as a coupling element of microwaves to the plasma. This approach enables that the wave-power is absorbed over a large plasma surface, which results in production of high-density plasmas of large volumes. The particular source designs differ only in the way of the coupling of microwave power into this resonator. Some of them couple the microwaves via the open waveguide structures [1,2] and the others use the slotted antenna or antenna arrays [3,4]. The outstanding parameters of these sources, in terms of plasma densities and temperatures, are unfortunately overshadowed by their resonant behavior, which results in the existence of a discrete set of plasma densities bound to the particular electromagnetic modes sustaining the discharge.

In this paper we present a design of the large area microwave planar plasma source, which has been developed in our laboratory. [8,9] Our source, similarly like most of the sources of its family, is based on the absorption of the energy of an electromagnetic wave propagating along the plasma-dielectric interface. Characteristic feature of presented design is that the microwave power is coupled into the dielectric resonator via the fully azimuthally symmetrical microwave applicator, a tunable cylindrical cavity with the annular slot antenna, which is considered to be more suitable for creation of azimuthally symmetrical discharges on large diameters. The resonant behavior of the source is controlled by an additional tuning system applied directly on the dielectric resonator. This tuning system enables also the control of the discharge diameter and the radial plasma density profile.

2. Description of the Plasma Source

The plasma source is schematically shown in **Fig. 1**. The vacuum part is a stainless steel chamber, cylindrical in shape, equipped with several ports for pumping, viewing and gas- and instrumentation-feedthroughs. The inner diameter and the height of the chamber are 312 and 350 mm, respectively. The top wall is a quartz plate with 15-mm-thickness and 350-mm-diameter. The microwave applicator is designed as a cylindrical cavity for TM_{011}-mode with the annular slot at its bottom wall and is placed in the center on the quartz plate. The cavity is made of aluminum cylinder with the inner diameter of 110 mm and the wall thickness of 5 mm. The bottom wall of the cavity is a 3-mm-thick and 100 mm in diameter aluminum disk, which together with the cylindrical body of the cavity forms an annular slot with the 5-mm-width and 110 mm outer diameter. The cavity upper-wall is a movable aluminum plunger, which is used as the main tuning mean.

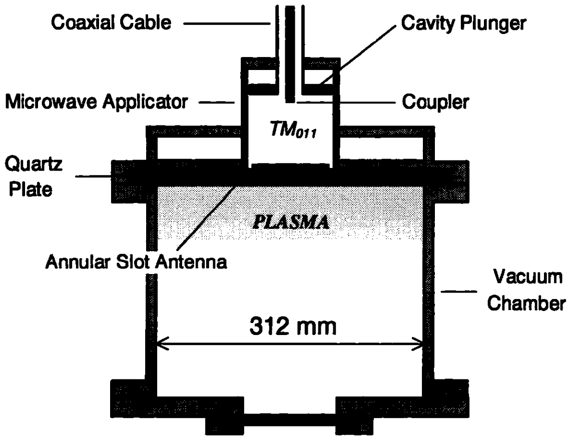

Figure 1. Cross-sectional schematic view of the plasma source

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The microwave power is fed into the cavity from the rectangular waveguide (WR-430) by a high power coaxial cable with the inner and outer conductor diameters 9 and 24.9 mm, respectively. To keep the azimuthal symmetry of the source, the cable enters the cavity from its top center and is terminated by a copper coupler with the diameter equal to the coaxial cable inner conductor diameter. The coupler penetration depth into the cavity is adjustable, what represents the second tuning mean. The quartz plate area out of the cavity is covered by aluminum plate, which was movable in axial direction and could represent another tuning mean. The rectangular waveguide line is equipped with a water-cooled isolator, two directional couplers and two power detectors enabling the monitoring of incident and reflected power. Whole system is powered by a stabilized 2.45 GHz magnetron-generator with the output power in the range from 200 to 3000W.

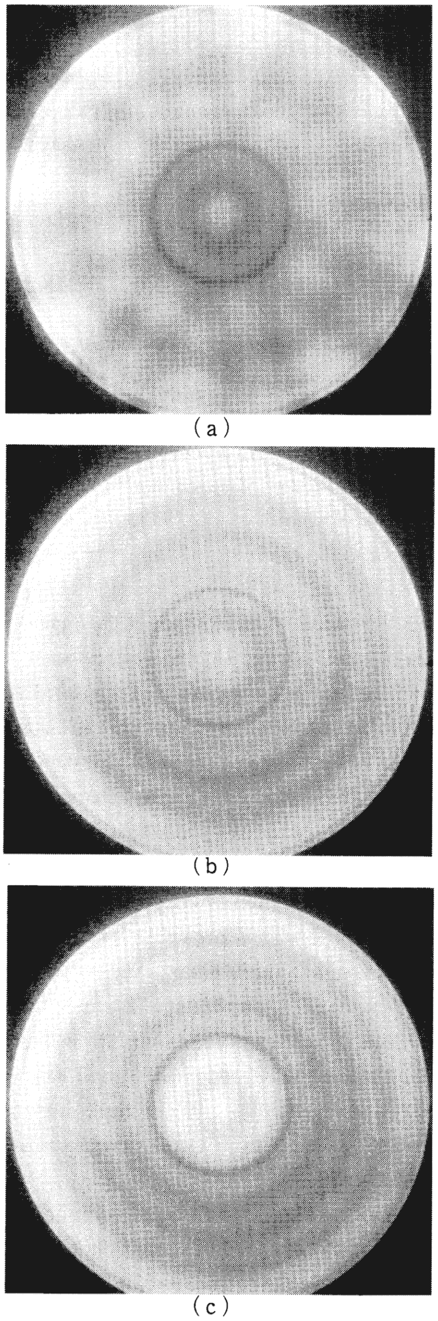
The vacuum chamber is pumped by a turbomolecular pump backed by a two-staged mechanical pump with the pumping speed of 900 m^3/hod. The base pressure of whole vacuum system is less than 10^{-6} Torr. The working pressure during the experiment is controlled by the mass flow controller and capacitance manometers.

The discharges were produced in argon gas with 99.99% purity in the range from 1 up to several Torr. The Langmuir probe used for the plasma density and electron temperature measurements was inserted into the chamber through the side-port in a 100-mm-distance from the quartz plate. The view-port at the bottom of the chamber, shielded against the microwaves by an iron mesh, was used for taking the images of the discharge light emission patterns.

3.Experimental Results and Discussion

3.1 Plasma Source Operation

The plasma source has been tested for argon in the pressure range from 1 mTorr up to several Torr. Above 30 mTorr the discharge ignition occurs immediately after the power is switched on or after some cavity plunger adjustment. The breakdown takes place on the axis of the applicator under the quartz plate. After the ignition, the plasma density increases in this place, the overdense plasma is formed, which creates the condition for self-consistent guiding of the electromagnetic wave. As a result, the discharge spreads radially out from the plasma chamber axis along the quartz plate filling the circular area with the diameter, which depends on the pressure and the absorbed power. When the discharge reaches the chamber wall, the wave-reflection occurs and standing wave is established. Therefore, these discharges are accompanied with the formation of various light emission patterns associated with particular electromagnetic standing wave modes. The modes sustaining the discharges are the eigen-modes of a self-consistent plasma-dielectric resonator, i.e. they depend on the geometry, dielectric constant and the boundary conditions of the resonator. The antenna, as a part of the boundary conditions, appears to have significant influence too. For a certain configuration, the mode is a function of only plasma dielectric constant, which involves plasma density, therefore, it changes with the gas pressure and absorbed microwave power. [10] The geometry of our source suggests the existence of various Bessel-like modes or their combinations. In **Figs. (a)-2(c)** we can see the examples of different light emission patterns of the discharges sustained at 200 mTorr. The difference between these discharges is in the absorbed microwave power and, therefore, also in the plasma density. The azimuthally asymmetrical discharge in Fig. 2(a) absorbed 1120 W and the ion density measured on the plasma chamber axis 100 mm under the quartz plate was 5.5×10^{12} cm^{-3}. For the azimuthally symmetrical discharges in **Figs. 2**(b) and 2(c) these values were 975 W and 4×10^{12} cm^{-3}, and 500 W and 1.2×10^{12} cm^{-3}, respectively. It has been observed that the azimuthal symmetry of the light emission patterns of these discharges is caused by the rotations of the azimuthally asymmetrical light emission patterns. [11]


(a)

(b)

(c)

Figure 2. Bottom view of the light emission patterns of argon discharges sustained at 200 mTorr: (a) azimuthally asymmetrical discharge with 1120 W of absorbed microwave power and ion density of 5.5×10^{12} cm^{-3}; (b) azimuthally symmetrical discharge with 975 W of absorbed microwave power and ion density of 4×10^{12} cm^{-3} ; (c) azimuthally symmetrical discharge with 500 W of absorbed microwave power and ion density of 1.2×10^{12} cm^{-3}. The densities are measured on the plasma chamber axis 100 mm under the quartz plate.

At higher pressures, typically above 1 Torr the discharges, in addition to the light emission pattern structures mentioned above, the constricted forms with the space-scale much smaller than the standing wave wavelength are appeared [**Fig. 3**]. At lower pressures, on the other hand, the light emission pattern structure becomes less pronounced and, typically below 30 mTorr, only diffusive light emission is observed [**Fig. 4**].

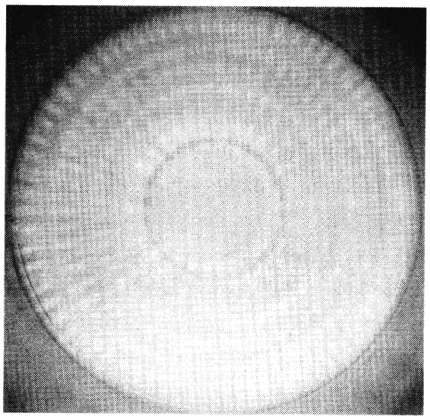


Figure 3. Constricted forms in the light emission pattern of argon discharge sustained at higher pressures; pressure p =10 Torr and the absorbed power P_A= 300 W.

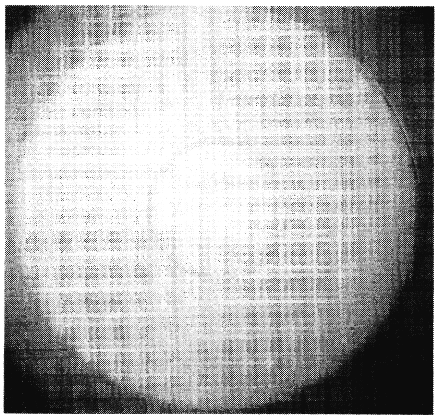


Figure 4. Diffusive form of argon discharge sustained at low-pressures; pressure p= 30 mTorr and the absorbed power P_A= 420 W.

The stable operation of our source at the pressures as low as 1 mTorr has been achieved. However, the ignition at such low pressures (no external triggering of the discharge is used) requires high powers and is not reproducible, sometimes even impossible. Therefore, for low-pressure operation, the discharges are usually started at the pressures above 30 mTorr and then the pressure is slowly decreased. Sometimes little adjustment of the tuning during this procedure is needed. With increasing pressure and/or decreasing microwave power, the diameter of the discharge decreases and at a certain condition the discharge can be localized only under the cavity with very strongly pronounced light emission pattern structure.

The discharge behavior and the electromagnetic modes sustaining the discharges at various experimental conditions are the subject of our current research.

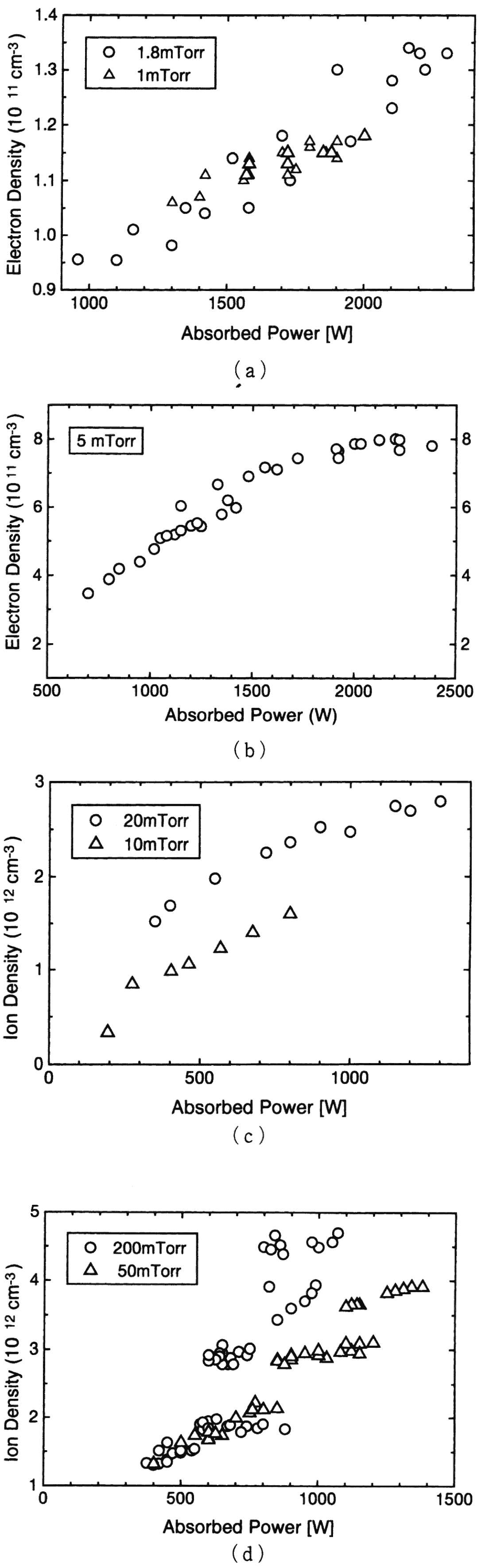


Figure 5. The dependence of the plasma density on the plasma chamber axis 100 mm under the quartz plate on the absorbed microwave power for argon gas: (a) 1 and 1.8 mTorr; (b) 5 mTorr; (c) 10 and 20 mTorr; (d) 50 and 200 mTorr.

3.2 Discharge Parameters

In **Figs. 5 and 6** are the plasma parameters of the argon discharges measured by the Langmuir probe positioned on the axis of the chamber, 100 mm under the quartz plate. The results show that within the investigated pressure and power range the plasma densities in the orders of 10^{11}-10^{12} cm^{-3} and the electron temperatures of 1.2-3.8 eV were achieved. At the pressures below 30 mTorr the plasma density increases roughly monotonously with absorbed microwave power [**Figs. (a)-5(c)**], but for higher pressures, a discrete set of plasma densities is measured [**Fig. 5(d)**], which are bound to the particular electromagnetic modes of the plasma-dielectric self-consistent resonator. Within one mode, the plasma density changes only slightly with power, however, significant jumps in plasma density are observed between the different modes.

Figure 6 shows the electron temperature dependence on absorbed microwave power. The temperature changes very slightly with the power and, at the pressures above 10 mTorr, also pressure does not have any significant influence on the electron temperature. Below 10 mTorr, however, the temperature increases quite considerably with decreasing pressure and, within the range from 10 mTorr to 1 mTorr, the values from about 1.2 to 3.8 eV were measured.

In the **Fig. 7**, the radial distribution of the electron density and the electron temperature in the 5 mTorr discharge, is shown. The density in the 100-mm-distance from the quartz plate has the Bessel profile, i.e. the discharge is in the diffusion-controlled regime. The temperature remains constant over the whole plasma source diameter.

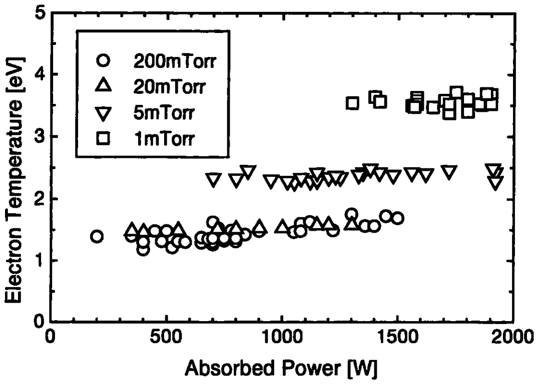


Figure 6. The dependence of the electron temperature on the plasma chamber axis 100 mm under the quartz plate on the absorbed microwave power for argon gas in the pressure range from 1 mTorr to 200 mTorr.

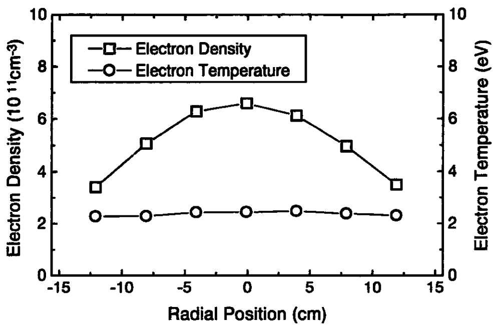


Figure 7. Radial profile of the electron density and the electron temperature in 5 mTorr discharge measured 100 mm under the quartz plate at the absorbed microwave power of 1400 W.

3.3 Tuning System

The resonant behavior of the plasma source, i.e. the density jumps associated with the mode jumps in the plasma-dielectric resonator, especially pronounced at the pressures above 30 mTorr, represents a serious deficiency for the plasma source operation. For the source stability, there is a demand for the smooth control of plasma parameters without any jumps. To achieve this, special tuning means have to be applied directly on the resonator. Indeed, by lifting the aluminum plate surrounding the microwave applicator, in a certain plasma density range, the continuos change of plasma density has been observed. [12] Recently, we developed a new tuning system, which is shown in the **Fig. 8.** [13] This tuning system consists of three tunable coaxial cavities, concentrically placed around the microwave applicator on the quartz plate. The cavities are made of aluminum cylinders with 5-mm-thick wall, and the coaxial sections have the inner and outer conductor diameters 120 and 180 mm (tuner cavity-1), 190 and 250 mm (tuner cavity-2) and 260 and 312 mm (tuner cavity-3), respectively. Each cavity is equipped with a movable shorting plunger. In the cross-sectional view, each cavity forms a T-junction with the quartz plate. The T-junctions are widely used in the conventional microwave transmission lines as the tuning elements, which enable the control of the power transmission from zero to 100% matching conditions. [14] The tuning system is under the way of investigation, however, the most recent results show that the properties of the T-junction can be usable also for the operation control of the microwave plasma source. As an example, **Fig. 9** shows the tuner cavity-1 plunger effect on the plasma density and reflection coefficient. In a certain plunger position, the complete matching condition is achieved, i.e. the reflected power is equal zero. On the other hand, a position of the plunger exists, when the tuner cavity stops the power transmission completely behind the tuner plunger, which results in the discharge diameter control [**Figs. 10(a) and 10(b)**]. In addition to these effects, an effect on the standing wave light emission pattern has been observed [**Fig. 11**], which could lead to the control of the radial plasma density profile in the source.

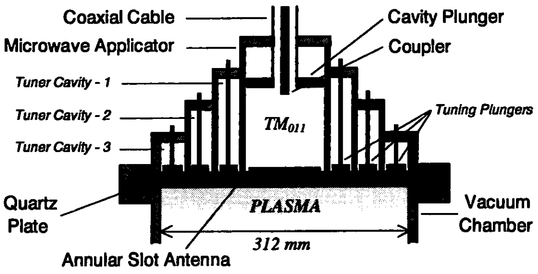


Figure 8. Cross-sectional view of the microwave applicator with the 3-coaxial-cavity T-junction tuning system.

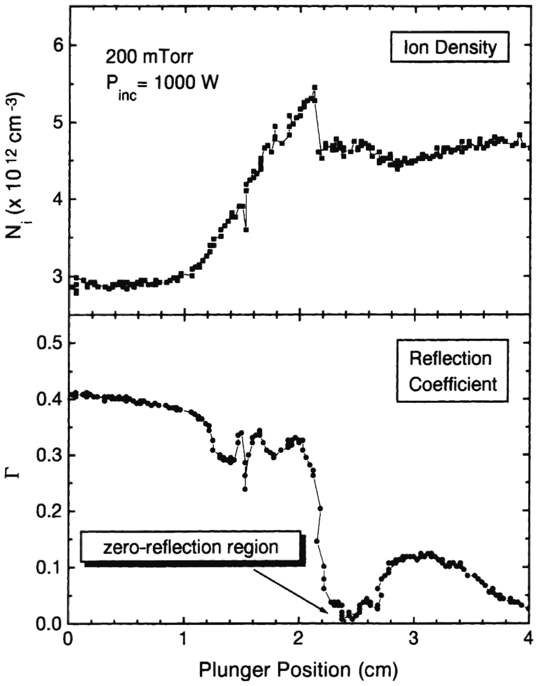
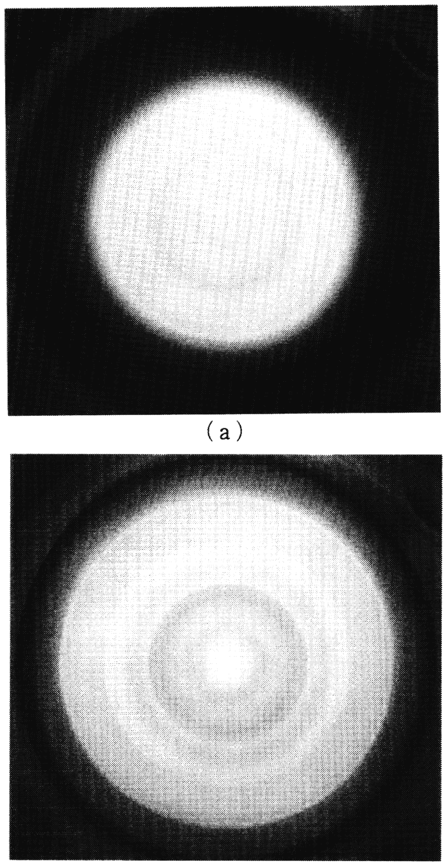


Figure 9. The effect of the plunger position of the tuner cavity-1 on the plasma density and the power reflection coefficient in 200 mTorr discharge. The density is measured on the plasma chamber axis 100 mm under the quartz plate. The forward microwave power is 1000 W.


(a)

(b)

Figure10. The localization of 200 mTorr discharge by the: (a) tuner cavity-1 plunger on the diameter of 180 mm; (b) tuner cavity-2 plunger on the diameter of 250 mm. The forward microwave power is 1000 W.

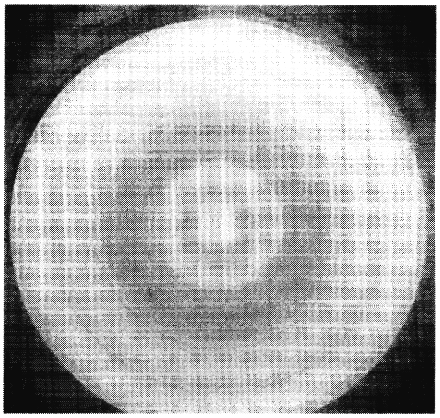


Figure11. The effect of the tuner cavity-1 on the light emission pattern of 200 mTorr discharge sustained by 600 W of absorbed microwave power.

4. Summary

This work presented the design, parameters and the basic features of the operation of the large area microwave planar plasma source developed in our laboratory. The source operates on 2.45 GHz microwaves and yields the plasma on the diameter of 312 mm. In argon, within the pressure range from 1 mTorr to 200 mTorr and microwave powers from 200 to 3000 W, the plasma densities in the orders of 10^{11} - 10^{12} cm^{-3} and the electron temperatures from 1.2 to 3.8 eV have been achieved. The plasma source exhibits the resonant behavior, especially pronounced at pressures above 30 mTorr, which results in the existence of a discrete set of plasma densities bound to the particular electromagnetic modes of the plasma-dielectric self-consistent resonator. Within one mode, the plasma density changes only slightly, however, significant jumps in plasma density are observed between the different modes. To avoid the density jumps and to achieve the continuous control of plasma density, a special tuning system is applied on the plasma source. In addition to the smooth plasma density change, this tuning system enables also the control of the discharge diameter and the control of the radial plasma density profile. Further research on the production and control of microwave discharges on large diameters is in progress.

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