High-pressure Microwave Discharges in a Compact Quartz Tube for an Electrodeless High Intensity Discharge Lamp

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A high-pressure microwave discharges in compact-size quartz discharge chambers were investigated in order to apply to high intensity discharge lamps. It could be ignited by low-power microwave using a launcher which is the annular slot antenna opened on the top plane of a coaxial waveguide. It was found that the discharge could be sustained by the microwave power of 10 ~ 30 W even at the atmospheric pressure of argon gas and that the microwave leakage from the discharge chamber was much lower than the warning level when the slot was opened in the most appropriated position. When the additives such as NaI and ScI₃ were mixed into argon in the discharge chamber, the light intensity emitted from the discharge significantly increased and the lamp efficiency estimated from the measured illumination amounted to 38.8lm/W. This value remained small because the ratio of discharge chamber volume to microwave power is much smaller than that of the conventional lamps.

Keywords : high-pressure microwave discharge, launcher, slot antenna, high Intensity discharge lamp, metal halide lamp

1. Introduction

Generally speaking, high-pressure discharges can generate intense enough light emission so that they are useful to apply to high intensity discharge lamps (hereafter abbreviated as HID lamps). Until now, the high-pressure sodium lamp, high-pressure mercury lamp, metal halide lamp and xenon short arc lamp have been developed and are in practical use as the external and interior lightings in the industries and in the various places of our daily life to light up grounds for outdoor-sports and/or roads for automobiles or the large-scale indoor-spaces of the buildings such as shopping centers, factories, schools and so on⁽¹⁾. These are based on their excellent properties such as high luminous flux, high lamp efficiency, high brightness and long lifetime, which lead to the low cost maintenance of lighting equipments and electric power consumption. However, the mercury-free discharge lamps with higher lamp efficiency and longer lifetime in comparison with the conventional HID lamps are urged to develop from the point of environmental problems of the earth.

Recently the novel types of HID lamps such as a sulfur lamp⁽²⁾ and a cluster lamp⁽³⁾ have appeared to meet the above requirements. The sulfur lamp in which atmospheric xenon is filled in the quartz together with a small amount of sulfur can be ignited by microwave higher than 200 W. It can provide the radiation with relatively good color rendering of 78 and high lamp

from the sulfur lamp is almost same as the spectral luminous efficiency of a standard observer. The cluster lamps have been developed based on the following phenomena that a lot of small soot (carbon clusters) produced in the candle flame can be heated to high enough temperature to radiate the visible light from the candle-flames in spite that the flame is not so high temperatures as much as 1200 K compared with the filament temperature of the incandescent lamps and that some kind of cluster such as WO₂Br₂ or Re₂O₇ can make a regenerative chemical cycle between the center and the surrounding of the discharge chamber induced by the heat convention in the high-pressure discharges, i.e., the cluster is decomposed at the high temperature at the center and is restored into the cluster at lower temperature near the wall of the discharge tube. In principle, the cluster lamps can emit high luminous flux and high lamp efficiency because their optimum operating temperature can be lowered than that of the conventional HID lamps.

The lamps mentioned above are designed appropriate to the purposes of large-scale lightings by consuming large electric power with high voltage so that it is difficult to apply them to the small-scale lightings. Recently, metal halide lamps with small-size⁽⁴⁾ have been developed for the head-lamps of the motor-car or the back-lighting of the liquid crystal display operated by the electric power lower than 50 W. These metal halide lamps are not only compact but also have the convenient equipments such as instant start electronic lamp and re-ignition circuits. The lamps can satisfy with the ECE standard regulation⁽⁵⁾ i.e., luminous flux of 3200 lm by electric power of 35 W which corresponds to the lamp efficiency of 100 lm/W and brightness of 5500 cd/cm². However, in order to improve the lamp properties much more, it is necessary to take into account of the application of high-pressure discharges without electrodes since the electrodes restrict the additives to improve the color rendering and lamp efficiency because of chemical reaction with electrode materials.

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Moreover, the heat conduction loss through the electrode supporting rods, which leads to the reduction of the lamp efficiency, can be completely suppressed. Nowadays, several kind of electrode-less discharge lamps⁽⁶⁾ driven by 13.56 MHz RF-power have been supplied into the markets owing to their properties of high lamp efficiency and long lifetime. The lamps are operated by the electromagnetic wave inductively coupled with the discharge chamber through one-turn coil. The lamp efficiency and lifetime have been improved but brightness is not strong enough compared with conventional HID lamps. On the other hand, most high-pressure electrode-less microwave discharge like the sulfur and the cluster lamps can be ignited using open-ended microwave cavities or parabolic antennas closed by a coarse metal mesh to shield out the electromagnetic wave leakage but still have several problems concerned with loose microwave coupling with the discharge chambers^{(7),(8)}.

Among several types of discharges generated by the electromagnetic wave, the surface wave excited discharge⁽⁹⁾ takes an advantage of the following points that over-dense plasmas can be generated at the wide range of the filling gas pressure in the discharge chamber of which configuration can be varied from long cylindrical quartz tube to coplanar flat chamber. The frequency range of electromagnetic waves applicable to the surface wave plasma production is ranged from RF to microwave through various launchers. However there is a problem that the electromagnetic wave leaks out from the discharge chamber because the surface wave plasma is produced just inside the chamber wall where the intense electromagnetic field propagates in the direction determined by the configuration of the launcher and the discharge chamber. This is the reason why application of the surface wave discharge to the lamps has not been carried out.

In the present work, a high-pressure microwave discharge in the compact quartz discharge chamber with typically 7 mm in diameter and 7 mm in the height was investigated to develop the compact HID lamp with high lamp efficiency and long lifetime. The discharge should be generated by the low-power microwave with 2.45 GHz and the microwave leakage has to be suppressed to the level smaller than the warning one⁽¹⁰⁾. It was verified in the present work that the discharge could be sustained near the atmospheric pressure of argon gas by microwave power lower than 30 W, supplied into the discharge chamber through the slot antenna at the top of a coaxial waveguide. The microwave leakage from the discharge chamber was examined by changing the shape and position of the slot antenna. It was found that it could be decreased much lower than the warning level under a certain configuration of slot antenna. However the lamp efficiency remains 38.8 lm/W^{(11),(12)} at the maximum measured in the case that small amount of NaI and ScI₃ were added into argon or xenon in the discharge chamber.

The lamp efficiency should be 100 lm/W for the practical use. It is considered that under the present experimental condition, the additives are not evacuated to high pressure because the wall temperature of the discharge chamber remained at 700 °C so that sodium (Na) and scandium (Sc) did not radiate the visible light with shorter wavelength as much as the metal halide lamps do. Therefore, the improvement of the lamp system should be focused on the evacuation of additives by increasing the discharge chamber wall temperature.

2. Experimental Apparatus

In order to establish the high-pressure microwave discharge without electrode in the compact discharge chamber, the launchers newly designed in the present work have been tested to know the discharge ignition and microwave leakage by using the sealed and unsealed discharge chambers.

2.1 Microwave Circuit Figure 1 shows the microwave circuit which has three-stub tuner and the movable plunger to fulfill the matching condition. The rectangular-coaxial waveguide converter is placed at the end of the standard rectangular waveguide to convert TE₀₁ mode to TEM mode. The 15 dB attenuator is inserted to decrease the microwave power since the minimum microwave power from the magnetron oscillator is around 200 W, which is too large to the present experiment carried out by the microwave power lower than 50 W.

2.2 Launcher The coaxial waveguide shown in Fig.2 is made of brass and the ratio of an outer diameter of an inner conductor to an inner diameter of an outer conductor is set at 3 in order to make the Joule loss caused by the microwave power propagating in the coaxial waveguide minimum. The length of the coaxial waveguide is 210 mm which corresponds to 6 times a quarter wavelength of the microwave in the free space for the node of the standing wave excited in the waveguide to coincide with the top of the waveguide as shown in Fig.3. The annular slot antenna opened on the top plane of the coaxial waveguide works as the launcher and the microwave can radiate outside from the waveguide through the slot antenna and make breakdown of the high-pressure gas in the discharge chamber placed on the launcher.

Fig. 1. Schematic diagram of microwave circuit

Fig. 2. Details of the launcher

Fig. 3. Launcher equipped on the rectangular waveguide

Fig. 4. Three type of the launcher to examine the ignition and microwave leakage

Fig. 5. Schematic diagram of the unsealed discharge chamber. The bottom part with 7 mm in diameter works as the discharge lamp

It is supposed that coupling of the microwave power into the discharge chamber becomes stronger, while the microwave leakage will increase as the slot antenna is opened out in the top plane of the coaxial waveguide. Therefore, three types of annular slot antenna with 1 mm wide called Slot A, B and C as shown in Fig.4 are designed in order to investigate the gas discharge efficiency and the amount of the microwave leakage.

2.3 Discharge Chamber The unsealed discharge chamber made of quartz cylinder with an inner diameter of 7 mm (a bottom part in Fig.5), is used in the experiment in order to investigate the pressure dependence on the discharge, where argon

Table 1. Specification of unsealed discharge chamber

Inner diameter (mm)	7
Height of chamber (mm)	7
Volume (mm ³)	270
Gas	Argon
Gas pressure (Torr)	55 ~ 760
Wall load at 20 W (W/cm ²)	8.7

Fig. 6. Schematic diagram of the sealed discharge chambers.

Table 2. Specification of sealed discharge chambers

Type of discharge chamber	A-1	A-2	B-1	B-2
Inner diameter (mm)	7	7	7	7
Height of chamber (mm)	10	10	7	7
Volume (mm ³)	270	270	154	154
Wall load at 20W (W/cm ²)	8.7	8.7	12.0	12.0
Argon (Torr)	1	300	1	300
NaI (mg)	2.5	0.45	2.5	0.45
ScI ₃ (mg)	2.5	0.45	2.5	0.45

is flowing in the chamber during the experiment. Table 1 notes the specification of the discharge chamber. On the other hand, the sealed discharge chambers are made of anhydrous quartz which consists of more than 99.99% SiO₂ with content of OH less than 100 ppm. To make the amount of OH in the quartz lower than a few ppm, the quartz is heated up at 1050 °C for one hour and then is cleaned up in the argon glow discharge to remove the impurities on the tube wall such as oxygen and water, which are considered to induce a blackening and a decrease in transparency of the quartz glass. After these procedures, the argon and additives of NaI and ScI₃ are included in the quartz tube. The details of the discharge chamber configuration and the contents filled in the discharge chambers are indicated in Fig.6 and Table 2 respectively.

3. Experimental Results and Discussion

At first, discharges generated by microwave power of 10 W were examined at the pressure from 50 to 760 Torr of argon using unsealed discharge chamber for three slots A, B and C. In each case of slot, the discharge could be generated at lower pressure but the slots A and B could sustain the discharge at the higher pressure. Figure 7 shows the pictures of the discharge. It is shown that the glow-like discharge could extend upward along the glass tube when the pressure is lower than 100 Torr, while the discharge was

Pressure (Torr)	55	100	200	400	500	600	760
Slot A							
Slot B							
Slot C							

Fig. 7. Discharge modes for slots A, B and C as a function of argon pressure (The Incident and reflected microwave powers are 20 W and 0 W, Camera: shutter speed-1/30, iris-F9.5)

Fig. 8. Schematics of the microwave leakage measurement

confined inside the discharge chamber and changed to the filamentary mode with increasing the pressure. The color of light emitted from the discharge was changed from red to blue with increasing the pressure, which may reflect the change of the electron temperature in the plasma.

The microwave leakage from the discharge chamber was measured by the Microwave leakage detector (Microdenshi Co.Ltd, LD10M) in such a way that the maximum value obtained by changing the direction of the detector probe placed at 50 mm from the discharge chamber as shown in Fig.8 was recorded as the microwave leakage. The warning and dangerous zones for human body specified by the Radio Frequency-Exposure Protection Standard⁽¹⁰⁾ are ranged from 2.0 to 5.0 mW/cm² and over 5.0 mW/cm² respectively. The measured microwave leakages for slot A, B and C are shown in Fig. 9 as a function of the pressure. It is found that microwave leakage decreases lower than 5 mW/cm² with increasing the pressure. This can be explained as follows; with increasing the pressure in the discharge chamber, more microwave power is consumed to sustain the discharge and the

Fig. 9. Microwave leakage for slots A, B and C as a function of the pressure

plasma density will become higher than the critical density such that $\omega = \omega_p$ of $7.0 \times 10^{11} \text{ cm}^{-3}$, because the skin depth δ at the higher pressure becomes comparable to the chamber radius so that the microwave can penetrate more deeply into the plasma with critical density, where ω_p and ω are the plasma and microwave frequencies. As is well known, δ at $v_e > \omega$ is given by $(c/\omega_p) \times (2v_e/\omega)^{1/2}$ ⁽¹³⁾, where c is the light velocity, and v_e is the electron collision frequency. Assuming the plasma density of 10^{14} cm^{-3} and $v_e \sim 10^{11} \text{ s}^{-1}$ for argon pressure of 100 Torr, $\delta \sim 2 \text{ mm}$. This means that microwave can penetrate into the half of chamber radius. Then the microwave will be effectively consumed for the high-density plasma production, which leads to the low microwave leakage. However, the slot antenna is opened in the outer regions of the discharge chamber, a part of the microwave

Table 3. Discharge properties radiated from the sealed discharge chambers

Type of discharge chamber	A-1	B-1	B-2
Illumination E (lx)	13.2	61	247
Total luminous flux F (lm)	41.5	192	776
Luminous efficiency (lm/W)	2.08	9.61	38.8
Brightness (cd/cm ²)	6.73	54.5	220.5

Fig. 10. Spectral profiles of the light emission from the discharge chamber B-2 ignited by the microwave of 20 W

propagating along the quartz chamber side wall can radiate from the chamber, which results in the microwave leakage increase.

The discharge properties of the sealed discharge chambers have been examined to know the possibility to the microwave discharge lamps without electrodes. Table 3 summarizes the experimental results ignited by the microwave power of 20 W, where the illumination E (lx) was measured by the luminance meter (Topcon, IM-3) placed at 500 mm from the discharge chamber. Total luminous flux F (lm) was calculated by equation: $F = 4\pi d^2 E$, derived under the assumption that discharge chamber is the spot light source with uniform luminous intensity of uniform spot light source, where d (cm) is the distance between the lamp and Illuminometer. It is seen that the best lamp efficiency of 38.8 lm/W and brightness of 220.5 cd/cm² are obtained by the discharge chamber B-2 which is the smaller volume and higher pressure among the tested discharge chambers in Table 2. However, they are by 1/3 and 1/30 times smaller than those of the metal halide lamps practically used for the automotive-headlamp, respectively.

The spectral distribution of the light emission from the discharge chamber B-2 was measured by the spectroscopy (Ocean Optics, Inc. S2000) and shown in Fig. 10. It is found that a lot of Na and Sc discrete spectral lines were observed. However, Na resonance absorption was not observed, which suggests that the pressure in the discharge chamber is not high enough. The wall temperature of the discharge chamber was measured by the thermocouple attached at the top of the discharge chamber and is shown in Fig. 11 as a function of time after the ignition. The wall temperature is saturated at 700 °C. Table 4 compared the pressure inside the chamber at three different wall temperatures of 27, 700 and 1000 °C. It is found that the wall temperature should be 1000 °C at least for NaI and ScI₃ to evaporate and to emit their own spectra from the discharge chamber. Therefore, in order to achieve high enough lamp efficiency for practical use, it is

Fig. 11. Temporal change of the wall temperature of the discharge chamber after the ignition

Table 4. Pressures in the discharge chamber of A-1, A-2 and B-2 calculated at three typical temperature. 700 °C is measured one

Temperature	Species	Pressure (Torr)		
		Type A-1	Type A-2	Type B-2
27°C	NaI	0	0	0
	ScI ₃	0	0	0
	Ar	1	300	300
	Total	1	300	300
700°C	NaI	1	1	1
	ScI ₃	3	3	3
	Ar	3	973	973
	Total	7	977	977
1000°C	NaI	44	44	44
	ScI ₃	544	544	544
	Ar	4	1273	1273
	Total	1773	1861	1861

necessary to increase the wall temperature by some reasonable ways. It is effective to improve the lamp efficiency by reducing the discharge chamber volume, which leads to increase in the brightness and luminous flux. In fact, this can be proved by the lamp data of the commercially supplied discharge lamps¹⁴⁾ for automotive-headlamp which radiate the luminous flux of 3200 (lm) by 35 W, where they have the spherical shape with volumes of 30 mm³ which is 9 times smaller than that of the present lamps around 270 mm³.

4. Summary

The stable discharge was sustained in the discharge chamber from 50 to 760 Torr of argon by applying 2.45 GHz microwave of 10 W ~ 30 W. The microwave leakage from the discharge chamber decreased to the level lower than the warning one for the human body with increasing the gas pressure higher than 200 Torr. The microwave coupling to the plasma is strong enough due to the large skin depth in the high-pressure plasma. Thus, the microwave power is consumed in the high-pressure plasma so that the microwave leakage from the plasma is significantly reduced. However, when a slot antenna is positioned outer region on the discharge chamber bottom plate, then the microwave propagating along the chamber side wall will radiate, which increases the microwave leakage.

The sealed discharge chambers filled with argon of 300 Torr together with NaI of 0.5 mg and ScI₃ of 0.5 mg was ignited by the

microwave power of 20 W. The measured lamp efficiency and brightness are 38.8 lm/W and 220.5 cd/cm², which are much smaller than those of the practically used metal halide lamps with electrodes. The wall temperature of the discharge chamber measured by the thermocouple was saturated at 700 °C which is lower than the most appropriate temperature of 1000 °C for NaI and ScI₃ to be evaporated and to make the visible light emission for improvement of the lamp efficiency, the brightness and color rendering property. The ratio of the discharge chamber volume to the electric power is 10 times for the present sealed discharge chamber larger than that for the practically used metal halide lamps. This suggests that the lamp efficiency and the brightness of the lamp will be improved to the practical level by reducing the volume of the discharge chamber because higher ratio of microwave power to the lamp volume will increase the lamp wall temperature and then the lamp luminous flux.

The experiment using the launcher with 60 mm long has been carried out to fit the practical use. It was found that the discharge properties were similar to those for the present launcher. The detail of the work will be reported by another paper.

In summary, it is confirmed that the high-pressure plasma can be sustained by the coaxial microwave applicator with simple structure by applying the moderate microwave power, which may serve to develop the novel microwave discharge lamp filled with high-pressure gas.

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References

- (1) C. Meyer and H. Nienhuis: "Discharge Lamps", Philips Technical Library, Kluwer Technische Boeken B. V., Deventer-Antwerpen (1988)
- (2) J. T. Dolan, M. G. Ury, and C. H. Wood: "A novel high efficacy microwave powered light source", 6th Int. Symp. on the Science and Technology of Light Source, Budapest University of Technology (1992)
- (3) Weber and R. Scholl: "A new kind of light-generatin mechanism: Incandescent radiation from cluster", *J. Appl. Phys.*, Vol.74, pp.607-613 (1993)
- (4) M. Shido and T. Hori: "Automotive Headlamp", *J. Illum. Engng. Inst. Jpn.*, Vol.85, No.12, pp.983-984 (2001)
- (5) ECE Regulation No.99: Uniform Provisions Concerning the Approval of Gas-Discharge Light Sources for Use in Approved Gas-Discharge Light Sources for Use in Approved Gas-Discharge Lamp Units of Power-Driven Vehicles (1995)
- (6) Nikkei Architecture, pp.216-217 (Nov. 12, 1990)
- (7) B. Weber and R. Scholl: "A New Kind of Light-generation Mechanism: Incandescent Radiation from Clusters", *J. Appl. Phys.*, Vol.74, pp.607-613 (1993)
- (8) A. Hoshi, K. Hashimoto, and K. Katase: "New Microwave Powered Electrodeless HID lamp with Vane-Type Resonator", 9th Int'l Symp. on the Science and Technology of Light Source, pp.83-84 (2001)
- (9) C. M. Ferreira and M. Moisan: "Microwave Discharges Fundamentals and Applications", NATO ASI Series, pp.427-444, Plenum Press, New York and London (1993)
- (10) Association of Radio Industries and Business Standard: Radio Frequency-Exposure Protection: RCR STD-38
- (11) T. Nakamura, M. Shido, A. Etoh, M. Kando, and H. Matsuo: "Application of microwave surface wave discharge to the electrodeless discharge lamps", Proc. of 16th ESCAMPIG/5th ICRP, Vol.1, pp.371-372, Grenoble, France (2002)
- (12) M. Shido, T. Nakamura, T. Serita, H. Matsuo, and M. Kando: "High-pressure Low-power Microwave Discharge using Annular Slot Antenna at the top of the Coaxial Tube", Proc. of 26th Int'l Conf. on Phenomena in Ionized Gases, Vol.2, pp.97-98, Greifswald, Germany (2003)
- (13) M.A. Lieberman and A.J. Lichtemberg: Principles of Plasma Discharges and Materials Processing, p.390, John Wiley and Sons, Inc. (1994)
- (14) Automotive discharge lamp D2R produced by Koito Manufacturing Co. Ltd, Shimizukitawaki 500, Shizuoka 424-8764 (2003)

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