Laser Diagnostics of Mercury-free Fluorescent Lamps for Investigation of Effects of the Auxiliary External Electrode*

Hideki MOTOMURA**, Kenjiro TORYU**, Tadashi MURAKAMI**, Masahiro OKAMOTO**, Yuko IMAI**, Terukazu MATSUGI** and Masafumi JINNO**

Abstract: The fluorescent lamps are widely used for general lighting because of their high efficacy, long life and so forth. However, fluorescent lamps in general contain mercury, which has a possibility to cause environmental problems. So we have been developing fluorescent lamps that contain only rare gases in place of mercury. The rare gas lamps are environmentally friendly, but its luminous flux and efficacy were lower than those of mercury lamp. Therefore, we have tried improving luminous flux of the rare gas lamp by expanding positive column. By winding an external electrode on the outside wall of the lamp that has multi anodes and single cathode, positive column expanded and luminous flux increased. The increase of metastable atoms and expansion of its radial distribution was confirmed by laser induced fluorescence method. It is found that the external electrode has an effect of field distortion leading to the positive column expansion. Finally, by connecting large resistance to limit the current flowing through external electrode, power consumption decreased and luminance of 13 000 cd/m^2 and luminous efficacy of 90 lm/W are obtained, which are comparable with those of mercury fluorescent lamps.

Key words: Laser induced fluorescence, Matastable atoms, Luminous efficacy, Mercury-free fluorescent lamps, Auxiliary external electrode

1. Introduction

Recently the interests in environmental issues have become stronger. In the filed of light sources, many efforts to reduce the amount of mercury used for fluorescent lamps and to develop mercury-free fluorescent lamps have been done by various researchers [1–4]. The authors have been also trying developing mercury-free fluorescent lamps using xenon pulsed discharge [5–12]. One of the most serious disadvantages of low-pressure xenon discharge lamps is the contraction of positive column, which reduces efficacy. In order to avoid this contraction and to obtain a diffuse positive column, the authors proposed a lamp that has multi-pairs of electrodes [9–12] and have achieved luminance of 10 000 cd/m^2 and efficacy of 50 lm/W; luminance is almost comparable with mercury fluorescent lamps, on the other hand the efficacy should be enhanced by more than 80%. To solve this problem we employed an auxiliary external electrode to expand a positive column to get more diffuse with multi pairs of electrodes and achieved increase in luminous flux and found that the optimum position of the external electrode is near the cathode [12]. In this paper the effect of auxiliary external electrode on the lamp with multi

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anodes and single cathode are shown and its mechanisms is studied by laser spectroscopic methods. Moreover, reduction of the power consumption and enhancement of efficacy is demonstrated.

2. Experimental setup

The schematic diagram of the lamps used in this study is shown in Fig. 1. Two anodes and a wide cathode were placed in the lamp. An auxiliary external electrode was installed to expand a positive column to get much more diffuse. The lamp tube is made of Pyrex glass. The inner diameter of the lamp is 26 mm and the distance between anode and cathode is 50 mm. The external electrode was wound at the position of 5 mm apart from the cathode. Xenon was introduced into the lamps at the pressure of 10.7 kPa. When measuring the properties of the phosphor emission, lamps with phosphor were also prepared; the inside wall of the glass tube was coated with mixture of three-bands white phosphor, which is mixture of NP-107, NP-220 and NP-360, the products of Nichia Corp.

The lamps were operated by pulsed discharge using the circuit shown in Fig. 2. In this circuit, the negative pulsed voltage is applied to the lamp. From the previous studies [9–12] the pulse repetition rate and the pulse width were set at 25 kHz and 2 μs respectively. At these values the positive column is stable and emits large luminous flux. Two 100-kΩ variable ballast resistors were used to make the currents flowing two paths at a same value and to limit the total current flowing the lamp. These were adjusted at about 70 kΩ. The current was measured as voltage drop by the 1-kΩ resistor. Luminous flux was measured by calibrated integrating sphere with radius of 50 cm.

As a first step of understanding mechanisms of the effect of the auxiliary external electrode, radial density distribution of one of the xenon metastable atoms ($1s_5$ in Paschen's notation) was measured by laser induced fluoresce (LIF) method. Detailed apparatus setup is described elsewhere [13]. Laser beam at 450.1 nm from the OPO (optical parametric oscillator, SOLAR Laser Systems, LP-603) pumped by Nd:YAG pulse laser (SOLAR Laser

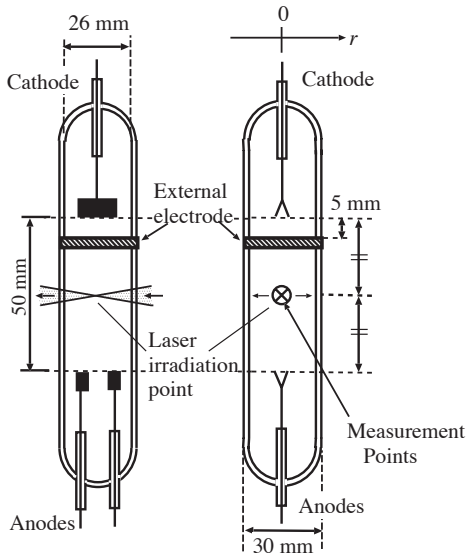

Fig. 1. Schematic diagram of the lamp with two anodes and a wide single cathode. An auxiliary external electrode was installed to expand a positive. The laser irradiation point for LIF measurement is shown together.

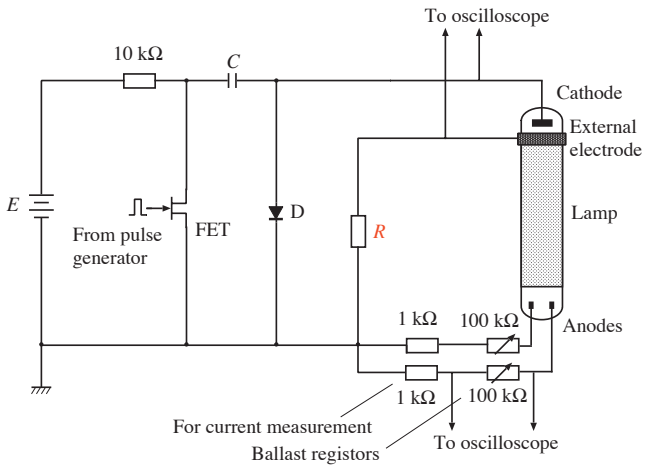

Fig. 2 Circuit diagram of the pulsed discharge for the lamp. The external electrode was connected to the ground, whose voltage is almost equal to that of the anode through a resistance *R*.

Systems, LQ-829) was focused on the center of the lamp by a plano-convex lens as shown in Fig. 1. The fluorescence at 764.2 nm was collected by a bi-convex lens. The collected fluorescent signal was detected by a PMT (photo multiplier tube) after passing a light guide and a monochromator, and its waveform was observed by a digital oscilloscope (Tektronix, TDS3054). The line width of the OPO was less than 0.1 nm and the pulse width of it was 10 ns. The excitation corresponds to the transition from $1s_5$ (measured metastable) to $2p_2$ level and the fluorescence corresponds to the transition from $2p_2$ to $1s_3$ (another metastable) level. The lamp and the collection lens were scanned across the optical path of the laser to get the radial distribution. The laser synchronized with the discharge pulse irradiated the lamp at the timing of the peak of the current pulse.

3. Results and discussion

3.1 The state and appearance of the positive column

Figures 3 and 4 show states of positive columns in diffuse and contracted states respectively. When the current is small, the positive column tends to diffuse as shown in Fig. 3. If the current is gradually increased, phosphor-converted visible emission will be gradually enhanced as well, however at a certain point the positive column suddenly contracts and phosphor-converted visible emission intensity and the efficacy suddenly drop. The photograph shown in Fig. 3 was taken just before the positive column changed its state from diffuse to contracted; at this point luminance of phosphor becomes highest in general. In this study the threshold value of the peak current through each anode, in which the positive column changed its state from diffuse to contracted was about 7 mA.

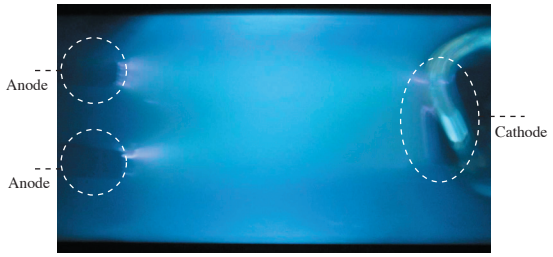

Fig. 3: A photograph of diffuse positive column without external electrode.

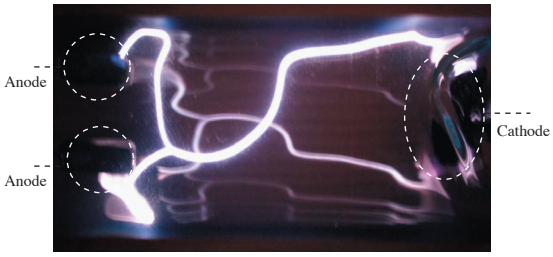

Fig. 4: A photograph of contracted positive column without external electrode.

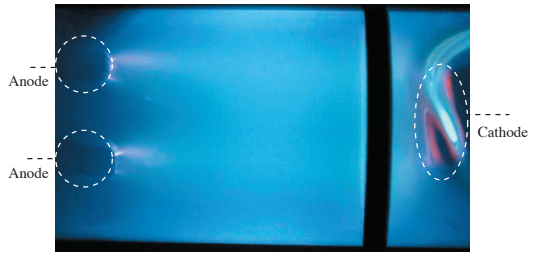

Fig. 5: A photograph of diffuse positive column with external electrode.

By winding an auxiliary external electrode on the outside wall of the lamp, the threshold values of current, voltage etc. between diffuse and contracted state changed, which is discussed in detail in the next subsection. Moreover, by using the external electrode the positive column expanded toward the glass wall and emission intensity from the positive column was enhanced compared with the case without external electrode as shown in Fig. 5, which was also taken just before the positive column changed its state from diffuse to contracted.

Figure 6 shows the radial distribution of the metastable atom with and without the external electrode measured by LIF method. It is found that the metastable atoms tend to gather toward one side without the external electrode whereas the distribution of the metastable atom becomes nearly symmetric by using the external electrode. Moreover, it is also found that the distribution of the metastable atom expands toward the glass wall and the total

amount of the metastable atoms increases by the external electrode. The metastable atoms generate excimers through three-body collision or are quenched to resonant atoms. That is one of the main generation processes of excimers or resonant atoms, which emit the vacuum ultraviolet radiation exciting phosphor. This change of behavior of metastable atoms is thought to be attributed to the improvement of the luminous flux. However, it is found that the change of behavior of the metastable atom is different when the lamp has only one pair of anode and cathode; the radial distribution did not change very much and the total amount of the metastable atoms increased by almost three times by an external electrode [14]. Further systematic investigation is necessary.

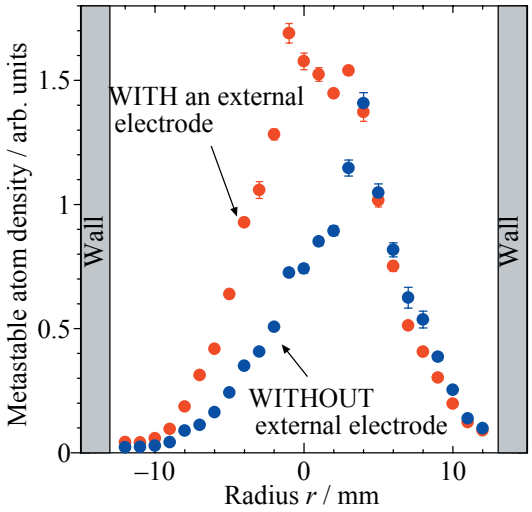

Fig. 6. The radial distribution of the metastable atom with and without the external electrode. It is found that the metastable atoms tend to gather toward one side without the external electrode whereas the distribution of the metastable atom becomes nearly symmetric by using the external electrode. Moreover, it is also found that the distribution of the metastable atom expands toward the glass wall and the total amount of the metastable atoms increases by the external electrode.

3.2 Improvement of luminous efficacy with an auxiliary external electrode

The threshold values between diffuse and contracted states changed by using the external electrode. The peak voltage decreased by using the external electrode by about 10%, whereas the peak current increased by about 10%. As the result, with the external electrode, consumed power by discharge between *internal* electrodes P_{in} was comparable or little bit small compared to that without the external electrode as shown in Fig. 7. On the other hand, luminous flux from the phosphor emission was enhanced by about 40% using the external electrode as shown in Fig. 8. Moreover, luminance at the center was measured simultaneously and was 13 000 cd/m^2, which is comparable with that of the mercury fluorescent lamps.

As shown above, by using external electrode the luminance can be enhanced. However, if the external electrode is directly grounded, discharge current between the cathode and the external electrode cannot be negligible and the efficacy drops by using the external electrode. To solve this problem, a large resistance was connected between the external electrode and the ground to restrain the current flowing through the external electrode. Power consumption through the *external* electrode decreased by increasing the resistance and became almost zero at 10 MΩ as shown in Fig. 9. It is found from Fig. 8 that the luminous flux is almost constant regardless of the value of the resistance. Thus, it became possible to improve the luminous efficacy up to about 90 lm/W as shown in Fig. 10, which is comparable to that of mercury fluorescent lamps.

3.3 Effect of the external electrode

Improvement of the luminous flux by the external electrode through the expansion of the positive column can be realized in two possible ways. One is a local field distortion around the external electrode leading to the expansion of the positive column, the other is a charge accumulation effect on the inside glass wall by the barrier discharge. However, only field distortion is effective when the resistance between the external electrode and the

ground is large and Figs. 9 and 10 show that the field distortion is effective and the barrier discharge effect is not necessary to improve the luminous efficacy.

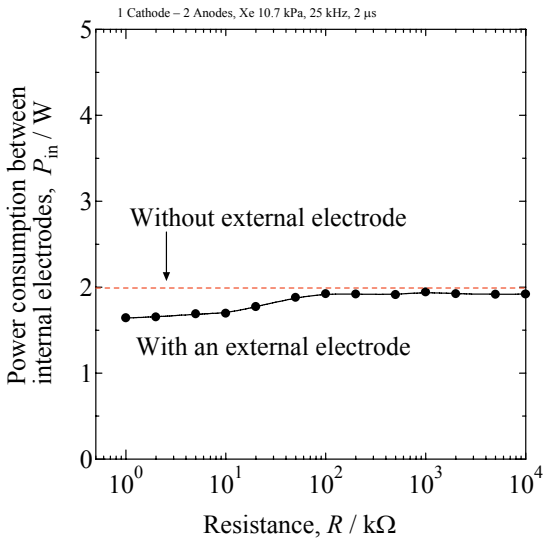

Fig. 7 Power consumption between *internal* electrodes just before the positive column changed its state from diffuse to contracted as a function of the resistance between external electrode and the ground. The value without external electrode is shown as a dashed line.

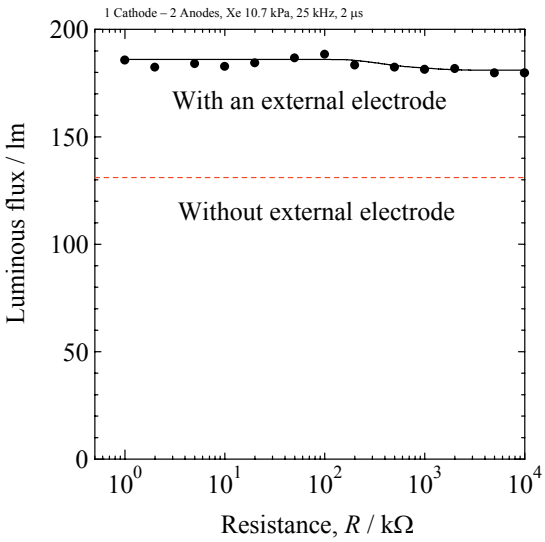

Fig. 8 Luminous flux just before the positive column changed its state from diffuse to contracted as a function of the resistance between external electrode and the gournd. The value without external electrode is shown as a dashed line.

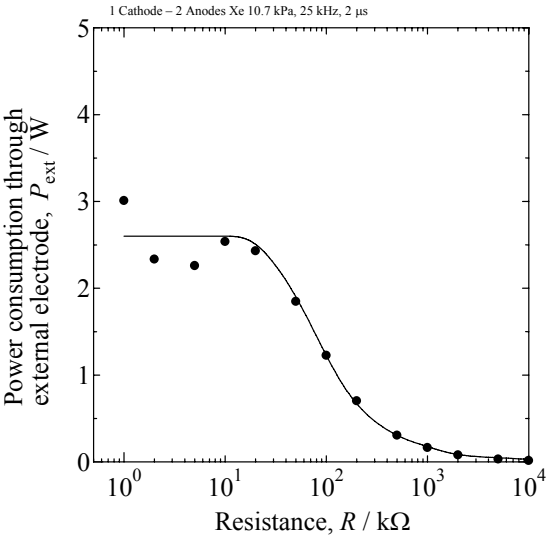

Fig. 9 Power consumption through *external* electrode just before the positive column changed its state from diffuse to contracted as a function of the resistance between external electrode and the ground. The value without external electrode is shown as a dashed line.

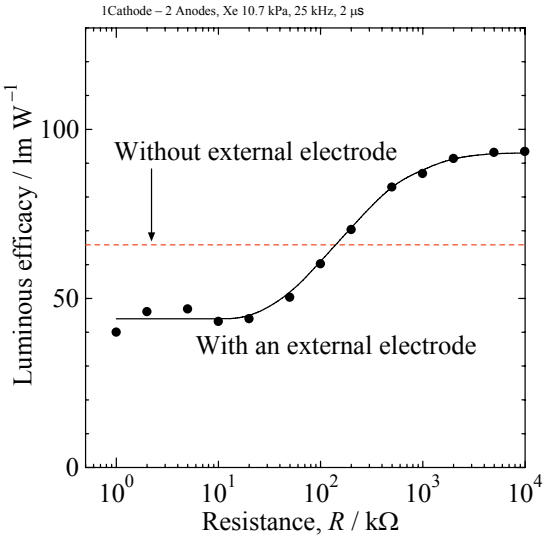

Fig. 10 Luminous efficacy just before the positive column changed its state from diffuse to contracted as a function of the resistance between external electrode and the ground. The value without external electrode is shown as a dashed line.

4. Conclusion

The luminance and flux of the mercury-free xenon cold cathode fluorescent lamps were increased by winding an auxiliary external electrode on the outside glass wall and connected to the ground through a resistance. The increase of metastable atoms and expansion of its radial distribution was confirmed by LIF method. It is found that the external electrode has an effect of field distortion leading to the positive column expansion. By increasing the resistance and restrain the current flowing through the external electrode, luminous efficacy was also enhanced and 13 000 cd/m^2 and 90 lm/W were achieved simultaneously, which are comparable with those of mercury fluorescent lamps.

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