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Magnetic Enhancement of Ultraviolet Radiation Efficiency of Low-Pressure Hg-Ar Discharge

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Abstract

Application of an axial magnetic field has been found to enhance the efficiency of production of resonance radiation in a low-density Hg-Ar discharge. A specialized experimental system was developed to study this effect, and a maximum efficiency increase of about 7% was observed at $B = 530$ gauss. The temperature for peak efficiency was observed to shift to higher temperatures in the presence of the magnetic field, as predicted by Richardson and Berman.

I. Introduction

In the time since the fluorescent lamp was introduced into the market, its luminous efficacy and color rendering properties have continually been improved (Refs. 1 and 2). The initial efficacy of 40 lumens per watt (lm/w) has been increased to over 100 lm/w with the latest advances in high frequency operation and the use of the rare-earth phosphors with narrow emission bands at 465 nm, 545 nm and 611 nm, respectively (Refs. 3 through 8). With the above phosphors color rendering indexes of over 80 have been achieved.

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Further increases in luminous efficacies may be possible by reduction of the fundamental loss processes in the plasma in which the electrical energy is converted to ultraviolet radiation. This ultraviolet radiation is converted into visible light by the phosphors on the lamp wall. One way to reduce these losses is to reduce the self-absorption of the resonance line of mercury (253.7 nm) within the lamp plasma (Refs. 9 and 10). A recent theoretical description of radiation transport in such a plasma (Ref. 10) has predicted a reduction in the losses due to self-absorption when the lamp is placed in an axial magnetic field. Furthermore, the theory predicts that there is an optimum magnetic field strength which will yield a maximum increase in the efficacy.

Initial measurements of the UV enhancement of a lamp in an axial magnetic field (Ref. 11) supported the theory. However, only a portion of the lamp was in the axial magnetic field and only a small portion of the UV radiation emitted was measured.

This paper describes an experiment directed at confirming the initial findings. An apparatus has been constructed in which the entire lamp is immersed in an axial magnetic field and all the UV emitted by the lamp is collected and measured by an integrating chamber. The change in the UV radiation produced by a mercury discharge tube is measured as a function of magnetic field and temperature. In addition to the variation of the efficacy, changes in the hyperfine structure of the 253.7 nm line were also examined for the above conditions.

The next section describes the experimental procedure. The results are presented in the third section followed by a discussion with respect to the Richardson-Berman model. The study is summarized in Section V.

II. Experiments on Magnetic Enhancement of Fluorescent Lamps

The effects of an external magnetic field on the emittance of resonance radiation from a low-pressure Hg-Ar discharge tube were observed in early 1983 at LBL. At that time, localized measurements of the radiance were carried out, namely the radiation from only one section of the lamp and from a restricted solid angle was detected. Figure 1 shows the augmentation of resonance radiation as a function of the applied magnetic field.

The angular distribution of the intensity from a low-pressure Hg-Ar discharge tube is different from that of a Lambertian radiator. In addition, the Zeeman components of the radiation are polarized. The quantum theory of the Zeeman effect (Ref. 12) shows that any level with angular momentum quantum number j splits into $2j + 1$ sublevels in a magnetic field. Each sublevel has its own magnetic quantum number m which takes on values differing by unity from $-j$ to $+j$. If m does not change ($\Delta m = 0$) in a radiative transition, then the line emitted is plane polarized parallel to the field. If m changes by one unit ($\Delta m = \pm 1$), the lines emitted

are circularly polarized as shown in Figure 2. The former situation corresponds to the π component, while the latter are σ components. Since an axial magnetic field can strongly influence the angular distribution of emitted UV, the net effect of the applied magnetic field can not be determined by the enhancement at one angle. Therefore, a compact integrating cylindrical chamber was designed to integrate either ultraviolet radiation or visible light when the external magnetic field is either present or absent. The apparatus for integrating measurements is shown in Figure 3. The external magnetic field was produced by a pair of Helmholtz coils of 10 inches inner diameter, and 14 inches outer diameter. The distance between the centers of these two coils is 6 inches. Correspondingly, the effective length of the uniform magnetic field is about 7 inches. The chamber fits inside the Helmholtz coils.

Discharge tubes with 7 inch arc lengths and 1.5 inches diameters were made of fused quartz. A discharge tube was mounted inside the integrating chamber (Figure 3). Provision was made to control the cold spot temperature of the discharge tube and, hence, to control the number density of mercury atoms. The chamber was heated by means of electric heating tape to ensure that the temperature of the remaining part of the tube was higher than that of the mercury reservoir. Ozone formation was prevented by maintaining argon flow within the chamber which also reduced the UV radiation absorption. A saturable reactance power supply provided the experimental lamps with a constant current of 430 ma.

III. Results

A. UV Radiation in a Magnetic Field

At specific cold spot temperatures from 30°C to 50°C the relative amount of UV radiation at constant current (the ratio of UV radiation with magnetic field to that without magnetic field) initially increases with increasing magnetic field strength. When the magnetic field strength reaches about 530 gauss, the increment of UV radiation reaches a maximum, and for larger values of the field the amount of UV radiation decreases with increasing magnetic field strength. In Figure 4 the UV measurements are expressed in terms of relative efficiency and show the variation of relative UV radiation efficiency with respect to the cold spot temperature for magnetic field strengths of zero, 210, 530 and 854 gauss. The data in Figure 4 are normalized to the value of the efficiency for zero magnetic field. We notice that the maximum value of UV radiation efficiency increase is about 7% when the magnetic field strength is about 530 gauss. The data also show that the temperature at which the maximum efficiency was obtained shifted toward higher values with increasing magnetic field strength.

B. Hyperfine Structure of the 253.7 nm Line

Some spectrograms of the hyperfine structure of mercury resonance line at 253.7 nm have also been obtained. The photographs were taken with a Jarrell-Ash 3.4 meter spectrograph (Figure 5) adjusted for observing the 253.7 nm line in the tenth order. A grating with 600 lines per mm was used so that the resolving power of the instrument was high enough to display the hyperfine structure of this line. The spectrograms of the hyperfine structure for the various magnetic fields and lamp wall temperature are displayed in Figure 6.

IV. Discussion

Natural mercury is composed of seven stable isotopes, and the resonance line of mercury has a hyperfine structure consisting of a series of lines whose separations are effects of both the resultant spins of nuclei and the differences of the masses of the isotopes. There is significant overlap of some of these lines and the line originating from ^{196}Hg is too weak to be observed. Consequently, the hyperfine structure of this line appears to be a five-line system at the resolution of our spectrograph. These five components can be clearly seen in the case of zero magnetic field and low temperature, as shown in Figure 6. As the cold spot temperature increases the density of mercury increases which leads to increased self-absorption and self-reversal of the lines. At constant temperature each component of the resonance line spreads due to Zeeman splitting as the applied magnetic field is increased. Therefore, the gaps between the components are gradually filled in by broadened lines.

The theory of Richardson and Berman (Ref. 10) predicted that an applied axial magnetic field would enhance the efficiency of a Hg-Ar discharge. This field splits the lines into their Zeeman components which reduces self-absorption losses. This effect dominates at weak fields and leads to an increased efficiency. At higher field strengths, ambipolar diffusion of ions and electrons is suppressed and the electron temperature is lowered. This effect competes with the Zeeman effect and leads to a maximum in the increase in the efficiency which we have observed at about 530 gauss. The fact that in a constant magnetic field the temperature of maximum efficiency became higher than in the absence of a magnetic field, is also consistent with the theoretical picture.

In addition to the temperature and magnetic field dependence described above, we have also observed an unusual dependence on the diameter of the tube. For a 1 inch and a 1-1/2 inch diameter the results are as we have described them. However, for a 5/8 inch diameter there is an initial dip in the efficacy as the magnetic field is applied. We are currently studying this effect.

V. Summary

The construction of an apparatus has permitted a series of experiments to measure the UV radiation from a low-pressure Hg-Ar discharge lamp at various axial magnetic fields and lamp wall temperatures.

The examination of the hyperfine structure has demonstrated the Zeeman splitting of the lines as well as the self-reversal at the elevated temperatures.

The measurement of the UV emission and input power shows an increase efficiency with an increasing applied magnetic field reaching a maximum at about 530 gauss. Their results support the predictions of the Richardson-Berman model.

Acknowledgement

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Figure Legends

- Figure 1. Augmentation of resonance radiation as a function of the axial external magnetic field strength.
- Figure 2. Energy level splitting and polarization of emitted lines due to Zeeman effect.
- Figure 3. Schematic diagram of the integrating cylindrical photometer.
- Figure 4. Relationship between relative radiation efficiency and cold spot temperature for several axial magnetic field strengths.
- Figure 5. Apparatus for observing the hyperfine structure of the mercury resonance line at 253.7 nm.
- Figure 6. Variation of the hyperfine structure at 253.7 nm with applied magnetic field strength and cold spot temperature.

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Figure 1. Augmentation of resonance radiation as a function of the axial external magnetic field strength.

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Figure 2. Energy level splitting and polarization of emitted lines due to Zeeman effect.

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Figure 3. Schematic diagram of the integrating cylindrical photometer.

XBL 8610-3863

Figure 4. Relationship between relative radiation efficiency and cold spot temperature for several axial magnetic field strengths.

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Figure 5. Apparatus for observing the hyperfine structure of the mercury resonance line at 253.7 nm.

-8°C

40°C

XBB-863-1843A

0 GAUSS

250 GAUSS

550 GAUSS

850 GAUSS

Figure 6. Variation of the hyperfine structure at 253.7 nm with applied magnetic field strength and cold spot temperature.

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