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E-H Mode Transition Properties of Cylindrical ICP Hg:Kr

Jong-Kyung Yang† **, Kwang-Hyun Pack*, Jong-Chan Lee** and Dae-Hee Park*****

Abstract - In this paper, we designed a cylindrical type light source having an electromagnetic principle of inductively coupled plasma, and measured its electrical-optical properties. Using the transformer principle, an electrically equivalent circuit cylindrical type light source was analyzed. According to the parameters of electromagnetic induction, which were diameter of coil with φ0.3~1.2mm, number of turns with 4~12 turns, distance with 40~120mm and RF power with 10~150W, the electrical and optical properties were measured. When the diameter of the coil was φ0.3mm, number of turns was 8 and distance was 40mm, and the maximum brightness of 29,730 cd/m^2 was shown with RF power 150W. The relationship between electromagnetic induction and plasma discharges was demonstrated using the mode transition from E-mode to H-mode

Keywords: E-H mode transition, ICP, Inductively coupled plasma

1. Introduction

There are certain light sources according to the principle of radiation, such as a thermally radiated light source, which radiates a stronger light than that of a block body at the same temperature when an object is heated, a cathode lay radiated light source, which radiates a cathode lay when a cathode lay impacts an object, and a radiated light source, which radiates a light due to the discharge caused by a collision between the charged particles, or between an atom and a molecular in gas/metal vapors. A discharge using a plasma state among these types can be classified as low pressure discharge products, such as a fluorescent lamp and a low pressure sodium lamp, and high pressure discharge products, such as a mercury lamp, high pressure sodium lamp, xenon lamp, and metal halide lamp [1].

A plasma discharge light source produces discharge using a chamber, which is filled with an inert gas, metal vapor, or its mixture, and sealed at each side, where electrodes are inserted through each sealed side, and voltage is applied between the electrodes. The light source using a plasma discharge can be classified as either glow discharge radiation or arc discharge radiation according to the applied voltage and current. These discharge light sources present certain disadvantages, such as reducing the lifetime by lowering a luminous flux maintenance factor and output due to the oxidized corrosion of electrodes, and reducing the gas purity when the light sources are used for many hours. Thus, a discharge tube, which has no electrodes inside the tube, such as an electrodeless light source can be used as a means to complement these defects.

An electrodeless light source can be classified as a CCP (Capacitively Coupled Plasma) or an ICP (Inductively Coupled Plasma) light source according to the principle of discharge. The CCP discharge produces discharge due to the ionization of gas, which is produced by an electric field when a high frequency power source is applied between the parallel plate electrodes. Conversely, the ICP discharge creates and maintains plasma by producing an electric field, which is generated using a time varied magnetic field created by an alternating field along the axial direction due to the current through the coil, in which the coil is wound around the discharge tube [2]. The merits of the ICP discharge can be summarized as follows; 1) A relatively high plasma density in a low voltage discharge, 2) Reduced impurities caused by the sputtering of electrodes, because the plasma generating discharge tube has no electrodes, 3) Uniformed plasma, and 4) Simple and easy structure formation.

Thus, this paper designed and produced a cylindrical light source based on the principle of the ICP type plasma radiation, and tested its electrical and optical properties. In addition, the cylindrical light source was formed as an equation by analyzing it using an electrically equivalent circuit based on the principle of a transformer. The physical and mechanical relations can be verified by understanding its electromagnetic and optical properties according to the change in the parameters of electromagnetic induction, such as the diameter of coil (φ0.3~1.2mm), number of turns (4~12 coils), distance (40~120mm), and the RF power (10~150W). In addition,

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the relationship between the electromagnetic induction and the plasma discharge was also verified through the transition property from an electric mode to a magnetic mode.

2. Experiments

The inductance of a magnetic induction coil used in the ICP can be varied by the shape of the coil according to Faraday's law, and significantly affects the spatial distribution of an electric field, which is induced by the current and the plasma. The brightness at the time the discharge is transferred from an electric mode to a magnetic mode by the RF power rapidly increased. The electric mode presented a low plasma density with a weak radiation in a wide area for the low RF power. This electric mode can be caused by an electric field, which is due to the voltage difference in each induction coil loop. The magnetic mode presented a rapid increase in electronic density and radiation according to an increase in the RF power. This increase is caused by the electric field of the vertical axis, which is generated by the resonance of the magnetic field. This magnetic mode generating a high density plasma can produce extremely different types of electrical and optical properties according to the shape of the inductance [3, 4].

As shown in Fig. 1, the inductance was calculated using Eq. 1 by varying the number of turns (N) from 4 to 12, in which the diameter (d) of the induction coil round a cylindrical pyrex discharge tube, which has the diameter of φ52.5mm and length of 250mm, was φ0.3 ~ 1.2mm, and its distance (I) was 40 ~ 120mm. In addition, the impedance was measured using an impedance analyzer (HP-4194A).

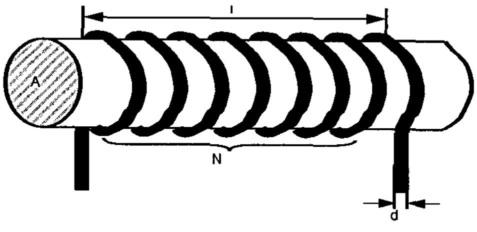
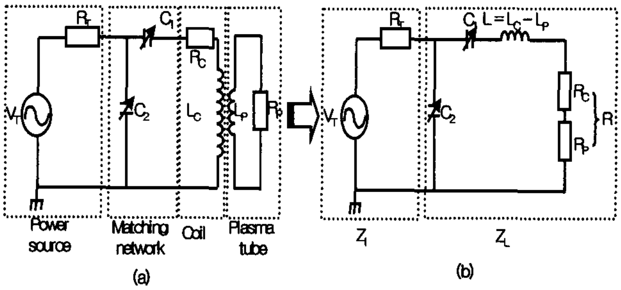


Fig. 1 Inductively coupled plasma discharge tube

Inductance is a constant, which represents the change in the magnetic flux generated according to the change in current, and is known as an inductance coefficient. The inductance can be expressed as Eq. 1. The inductance of the cylindrical pyrex discharge tube used in this experiment utilized an air-core coil, and was calculated by substituting the relative magnetic permeability rate of $4\pi \times 10^{-7}$H/m in a vacuum (μ_r) and free space (μ_0) into Eq. 1. The magnetic flux generated by the induction coil surrounding the discharge tube presents an index for the amount of magnetic flux in a specific sectional area, in which the value can be varied according to the diameter of coil (d), number of turns (N), permeability (μ_r), and distance between the coils (I) [5].

$$L = \frac{\mu_r \mu_0 N^2 A}{l + 0.45d} \qquad (1)$$

The ICP discharge generated a magnetic field according to the change in the current through a coil based on Faraday's law when the RF power of 13.56MHz was applied. The plasma can be generated and maintained by ionizing the neutral molecular due to the acceleration and collision of free electrons using an electric field, which is generated by the time varied magnetic field. Fig. 2 presents electrically equivalent circuits for a magnetic mode of the discharge tube used in this experiment. The equivalent circuit consists of four elements; 1) RF power to apply the high frequency to the discharge tube, 2) Impedance matching circuit to effectively transfer the output and implement a plasma state, 3) Induction coil, and 4) Discharge tube to generate the plasma.



(a) (b)

Fig. 2 Electrical equivalent circuit of an ICP discharge tube

Fig. 2(a) presents an electrically equivalent circuit. The RF power of 13.56MHz consists of a voltage source of V_T and output impedance of R_T for a coaxial cable, and the induction coil consists of an inductance element of L_C and resistance element of R_C. There are various types of matching circuits between the RF power source and the inductance coil RF. The circuit used in this experiment was a L-type circuit, which connects two variable capacitors of C_1 and C_2. The inductance element was not used in this circuit because the inductance may cause a factor of output loss. In addition, the discharge tube was also expressed as an inductance element of L_p and resistance element of R_P. The equivalent circuit as shown in Fig. 2(a) can be simplified as presented in Fig. 2(b). The RF power is to be satisfied as an equation, such as expressed in Eq. 3 in order to transfer the maximum output of the plasma when the RF power source and remaining sources are simplified as an output impedance of Z_1 and load impedance of Z_L, respectively [3, 6].

$$Z_L = Z_I \tag{2}$$

In this case, the impedance of the output of the impedance matching circuit can be calculated using Eq. 3.

In order to satisfy Eq. 2, the value of Z_L expressed in Eq. 3 should be equal to the impedance of R_T (50Ω) for the coaxial cable.

$$Z_L = \cfrac{1}{\left(\cfrac{1}{R + j(\varpi L - \cfrac{1}{\varpi C_1})}\right) + j\varpi C_2} \tag{3}$$

When a derivation was attempted to obtain this condition, the equation for the two variable capacitors could be expressed as Eq. 4 and Eq. 5, respectively. Thus, the condition for Eq. 2 can be satisfied by varying the capacitors of C_1 and C_2.

$$C_1 = \frac{1}{\varpi} \frac{\varpi L + \sqrt{\frac{R}{R_T}}\sqrt{(\varpi L)^2 + R(R - R_T)}}{(\varpi L)^2 + R^2} \tag{4}$$

$$C_2 = \frac{1}{\varpi}\sqrt{\frac{R}{R_T}} \frac{1}{\sqrt{(\varpi L)^2 + R(R - R_T)}} \tag{5}$$

As presented in Eq. 4 and Eq. 5, because the capacitors of C_1 and C_2 are defined by the values of the resistance (R) and inductance (L) of the induction coil, changes in the parameter of the induction coil become an important factor in defining the property of the cylindrical ICP.

In order to verify the optical and mode transferable properties according to change in the RF power and induction coil parameters, experimental equipment was configured as illustrated in Fig. 3.

Krypton gas, which has the purity of 99.999%, was filled with 0.15Torr as a buffer gas inside the discharge tube, and amalgam (Bi:Sn:Hg =48.6:36.4:15.0wt %), which is a major material in UV radiation, was also filled inside the discharge tube. The RF power was applied at 10 ~ 150W with the unit of 10W. The reflection power was controlled by varying the variable capacitors of C_1 and C_2 in the matching circuit in order to satisfy Eq. 3, and the impedance was also controlled to configure the reflection power within the range of 1%. The brightness was measured at a 1m distance from the source using a luminance meter (Minolta LS-100) by varying the inductance factor, such as the diameter of coil (d), distance (I), number of turns (N), and other factors. In addition, plasma properties were examined according to the values of inductance by verifying the transition power from the electrical mode to the magnetic mode.

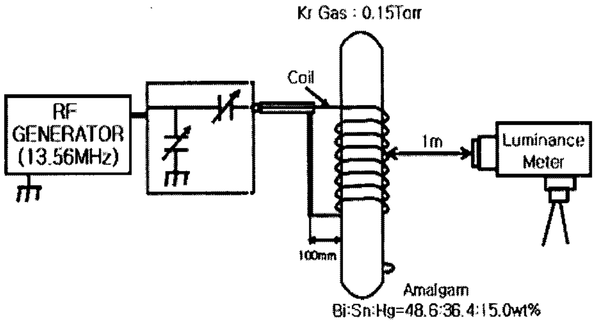


Fig. 3 Schematic Diagram of Experimental Equipment

3. Results and Considerations

Fig. 4 presents a comparison of the inductance, which was calculated using Eq. 1 according to the change in the diameter of the induction coil, and the measured value using an impedance analyzer (HP-4194A). The calculated and measured values correspond to one another almost perfectly, and the inductance decreased by 1.9~1.7μH according to the increase in the diameter of the induction coil. The brightness property was verified by varying the RF power from 10W to 150W with the unit of 10W according to the change in the diameter of coil under these conditions. In addition, the mode transition power from the electric mode to the magnetic mode was also investigated. The brightness property was measured using specific configurations, such as the 100mm fixed value of the coil distance and 8 coil turns, and the varied value of the coil diameters from φ0.3 to 1.2mm with the unit of φ0.3mm. Generally, the brightness property presented a rapid change when the mode was transferred to the magnetic mode. Consequently, in the case of the diameter of φ0.3mm, the brightness presented the highest value of 23,090cd/m^2 at 150W, and the transition power to the magnetic mode was decided at 140W, which showed a higher power than that of 120W for the diameter of φ1.2mm.

The electric mode is a type of ICP, which is generated by the voltage difference between the output section of the induction coil and the earth of the discharge tube. In this process, the voltage at the output section of the induction coil vibrated, and induced the vibration of the sheath, which existed inside the plasma. Then, electrons obtained ionization energy due to the vibration of the sheath. Fig. 6 (a) presents the lighting of the discharge tube in the electric mode at 100W of RF power, in which the discharge property is generally presented as dimness. The distributions of the electric mode that represent the brightness, as shown in Fig. 5 and Fig. 6, present a reduced value in the RF power from 140W to 120W according to the increase in the diameter of the induction coil. The magnetic mode is a type of ICP, which is generated by an electromagnetic wave induced by the vibration of the induction coil where electrons absorb energy. Fig. 6 (b) presents the discharge property in the magnetic mode at 140W of RF power, in which the magnetic mode indicated a high brightness and stable discharge property that differed from the electric mode. The RF power in the electric mode, which presented a brightness exceeding 18000cd/m^2, increased from 140W to more than 120W according to the increase in the diameter of the induction coil from φ0.3mm to φ1.2mm. As a result, the increase in the diameter of the induction coil decreases the inductance, and expands the turning point from the electric mode to the magnetic mode.

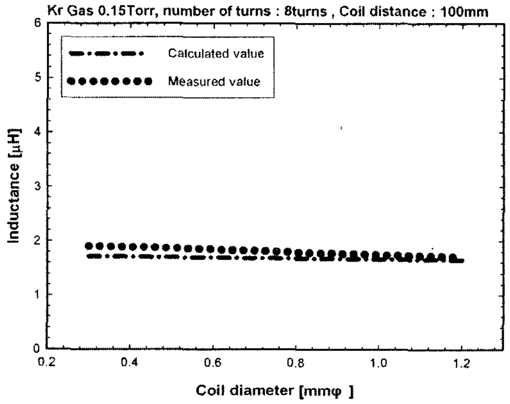


Fig. 4 Inductance Dependency for the Coil Diameter

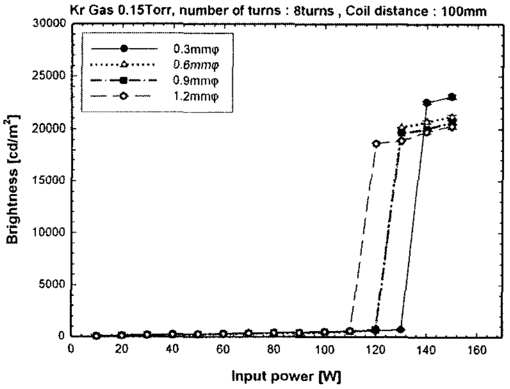
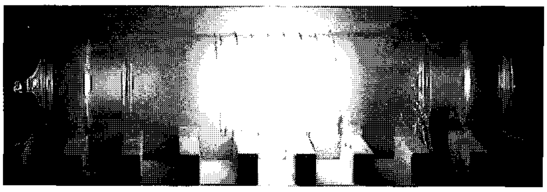


Fig. 5 Brightness Dependency for the Coil Thickness and RF Power

(a) E – mode



(b) H - mode

Fig. 6 Discharge Characteristics in the E-mode / H-mode

Fig. 7 presents a comparison between the calculated inductance and the measured value according to the change in the turns of the inductance coil. The calculated and measured values correspond almost perfectly with the results shown in Fig. 4, where the inductance presented a relatively large increase, such as 0.76~4.51μH, according to the increase in the turns of the induction coil.

Fig. 8 presents the brightness property and mode transition power when the RF power of 10~150W was applied by the unit of 10W according to the change in the turns of the coil based on the change in the inductance condition. The coil used in this case had a diameter of φ0.3mm, which exhibited the highest brightness as presented in Fig. 5. The brightness was measured under the conditions where the entire distance of the coil was fixed as 100mm, and the turns of the coil varied from 4 to 12 turns. The brightness property presented a high value of 23,090cd/m^2 when the RF power was applied at 150W, and the turns of the coil was 8. The transition to the magnetic mode was performed at a high power level according to the decrease in the turns of the coil, and the transition was performed over 230W when the turns of the coil were 4~6 turns. This method increased the relative magnetic flux density according to the increase in the turns of the coil for a specific distance. The increased magnetic flux density strengthened the energy transition rate of the electro-magnetic wave, which was induced through the induction coil. Thus, the mode transition can be performed at a low power level. As a result, the dependency of the change in the coil turns was significantly accentuated, as presented in Fig. 8, in comparison to the mode transition power according to the change in the diameter of the coil.

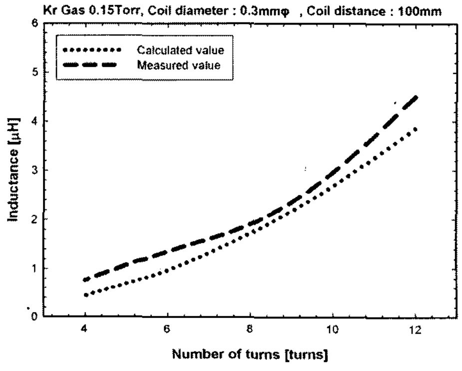


Fig. 7 Inductance Dependency for the Coil Turns

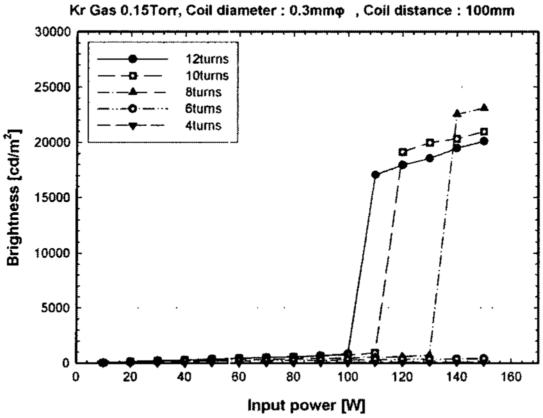


Fig. 8 Brightness Dependency for the Coil Turns and RF Power

From the verification of the inductance property according to the change in the coil distance from 40mm to 120mm with the unit of 20mm, the inductance decreased by 4.4 ~ 1.7μH according to the increase in the coil distance as shown in Fig. 9.

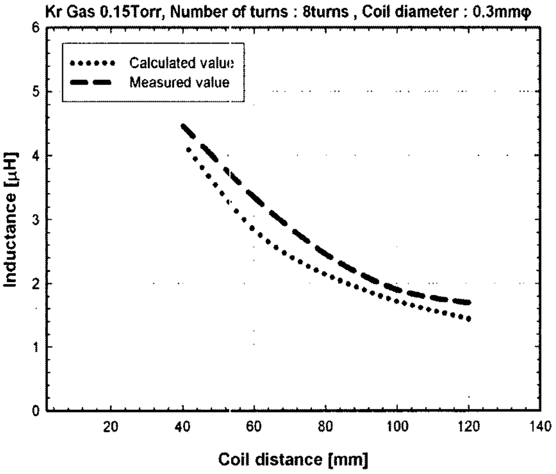


Fig. 9 Inductance Dependency for the Coil Distance

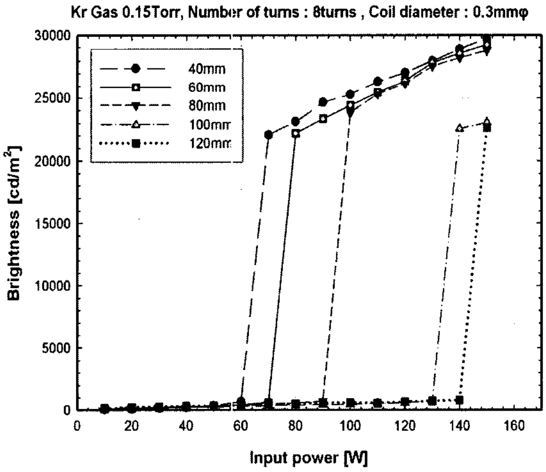


Fig. 10 Brightness Dependency for the Coil Distance

Fig. 10 presents the brightness property and mode transition power by increasing the RF power up to 10 ~ 150W with the unit of 10W according to the change in the coil distance. The brightness property according to the change in the coil distance was investigated based on the brightness conditions indicating that the coil diameter of φ0.3mm as presented in Fig. 5, and the coil turns of 8, as presented in Fig. 9, presented the highest brightness, respectively. The brightness property showed the highest value of 29,730cd/m^2 when the RF power of 150W was applied at 40mm according to the increase in the coil distance from 40mm to 120mm with the unit of 20mm. In addition, the transition power to the magnetic mode significantly decreased from 150W at 120mm to 70W at 40mm. The magnetic mode transition was performed at a low power due to the increase in the magnetic flux density and electromagnetic wave radiation in the induction coil as the number of harmonic flux increased according to the decrease in the coil distance.

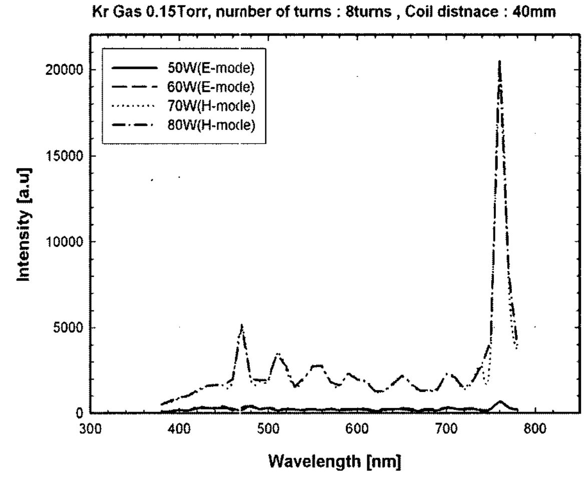


Fig. 11 Spectrum Intensity Dependency for the RF Power

Fig. 11 presents the spectrum property according to the change in the RF power under the conditions that the coil diameter was φ0.3mm, coil turns were 8, and coil distance was 40mm. In particular, the spectrum strength in the region of visible light presented a rapidly increased value at the mode transition region, such as 50 ~ 80W, where the mode transition from the electric mode to the magnetic mode was performed at 70W. In addition, the spectrum strength rapidly increased at the wavelength of 473.9nm and 760.1nm [6].

4. Conclusion

This paper designed and produced a cylindrical light source based on the principle of the ICP discharge, and investigated its electrical and optical properties. The cylindrical light source was analyzed as an equation using an electrically equivalent circuit based on the principle of a transformer. In addition, the physical mechanism was investigated by understanding the electromagnetic and optical property according to the change in the electromagnetic induction parameters, such as the coil diameter (φ0.3~1.2mm), coil turns (4~12 turns), and coil distance (40~120mm), and the RF power from 10W to 150W.

1) The inductance was calculated and measured using a cylindrical pyrex discharge tube, which had the diameter of φ52.5mm and length of 250mm, in which the discharge tube was rounded using an inductance coil, which has some variables, such as the coil diameter (d) of φ0.3~1.2mm, coil distance (I) of 40~120mm, and coil turns (N) of 4 ~ 12 turns.

2) The inductance decreased by 23,090cd/m^2 when the coil diameters ranged from φ0.3 to 1.2mm with the unit of φ0.3mm. In the case of the diameter of φ0.3mm, the brightness presented the highest value of 23,090cd/m^2 at 150W. The transition to the magnetic mode was performed at 140W, which was a higher power level than 120W of the coil diameter of φ1.2mm. The increase in the diameter of the induction coil decreased the inductance, and expanded the turning point from the electric mode to the magnetic mode.

3) The brightness property presented as a high value of 23,090cd/m^2 when the RF power was applied by 150W, and the turns of the coil was 8 under the fixed coil distance of 100m with the coil diameter of φ0.3mm. The reason that the transition to the magnetic mode was performed at the high RF power according to the decrease in the coil turns was due to the relative increase in the magnetic flux density according to the change in the coil diameter. In addition, the dependency of the change in the coil turns was significant, as expressed by the comparison of the mode transition power according to the change in the diameter of the coil.

4) The brightness property presented the highest value of 29,730 cd/m^2 when the RF power of 150W was applied at 40mm according to the increase in the coil distance from 40mm to 120mm with the unit of 20mm under the fixed value of the coil diameter of φ0.3mm, and coil turns of 8 turns. The magnetic mode transition was performed at a low power due to the increase in the magnetic flux density and electromagnetic wave radiation in the induction coil by increasing the number of harmonic flux according to the decrease in the coil distance.

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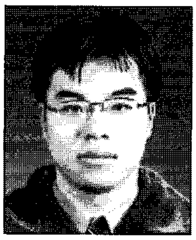

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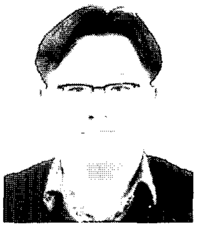

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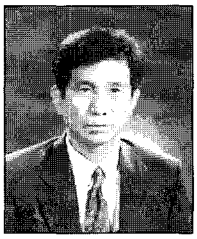

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