Sensors and Materials, Vol. 13, No. 8 (2001) 477–486
MYU Tokyo

S & M 0463

Optical Current Measurement System Using Faraday Crystal, Polarization-Maintaining Fiber and Faraday Rotator (Theory and Experiment)

Takashi Hirose, Tatsuo Takada and Yoshihiro Murooka[1]

Musashi Institute of Technology,
1-28-1 Tamazutsumi, Setagaya-ku, Tokyo 158-8557, Japan
[1]Shibaura Institute of Technology,
3-9-14 Shibaura, Minato-ku, Tokyo 108-8548, Japan

(Received March 14, 2001; accepted September 14, 2001)

Key words: optical measurement, Faraday effect, polarization-maintaining fiber, Faraday rotator

With advancing opto-electronic techniques, a current sensor consisting of a Faraday crystal has attaracted great interest for measuring currents flowing at a high potential, such as in a UHV (ultra-high-voltage) transmission line, because the Faraday crystal is a kind of insulator having optical transparency for the laser beam. But there are some problems in system stabilization, for example: intensity fluctuations of the light source, the birefringence of optical elements and also optical strains in the longer fiber cable. Therefore, we have developed a new current measurement system associated with both azimuth angle modulation and P- and S-polarized light division methods.

1. Introduction

Since the beginning of this century, power transmission line voltage has been doubled every twenty years with the increasing demand for electric power. Even though a 500 kV transmission line voltage was established in 1972 in Japan, it is expected that the transmission line voltage will be increased up to UHV, 1,000 kV class, in the near future. When the UHV transmission line system is realized, it will be necessary to develop both optical current and electric field measurement systems in which the longer fiber cable is adopted for isolating the optical current or the electric field sensor located at the high potential from the main part of the system located at ground.

In 1980, an optical current sensor involving the Faraday effect was initially devised and proposed for measuring currents flowing in the power system by Sato and co-workers.(1)

Later, Faraday current sensors associated with optical fiber cables(2–6) and fiber-optic current sensors(7–11) were developed. In 1985 Hidaka and Murooka succeeded in directly measuring the electric field distribution in and around both leader corona and leader in the long gap discharge using a Pockels field sensor associated with the longer fiber cable.(12) Later, Murooka and Nakano developed a simplified Pockels field measurement system having both high accuracy and sensitivity, using an intensity modulation method together with a dielectric mirror technique.(13,14) From this, it was expected that a similar technique could be developed for the measurement of currents flowing in the high potential area. Recently, we found that even though the optical current measurement system consisting of a Faraday sensor had been developed using the P- and S-polarized light division method(4) there are some problems such as system stabilization when the longer fiber cable is inserted into the optical current and electric field measurement systems. Therefore, we have succeeded in developing a new type of current measurement system with both azimuth angle modulation and P- and S-polarized light division methods, with which the intensity fluctuation of the light source, the birefringence of optical elements and characteristic differences between the two detectors can be eliminated. This has been proved theoretically and experimentally.(15,16) From a series of experiments, it is found that the present current measurement system is useful for precisely and accurately measuring not only AC but also DC currents flowing at high potentials.

2. Principle

As is well-known, when polarized light is irradiated onto a Faraday crystal which is inserted in a magnetic field the wave plane of the polarized light is rotated. Here, the rotated angle is proportional to both magnetic field intensity and the path length of light in the Faraday crystal. In the case of a magnetic field H produced with a current coil, the rotation angle $\Delta\phi$ is defined as follows;

$$\begin{aligned}\Delta\phi &= vHd \\ &= vNId. \end{aligned} \tag{1}$$

Here, v is the Verdet constant, d is the thickness of the Faraday crystal, I is current and N is the number of coils in the rill. By precisely measuring the rotation angle, it is easy to measure not only heavy currents flowing in the high potential area but also small currents, because the Faraday crystal having transparency for the laser beam is a kind of insulator. However, in the case of adapting a longer fiber cable into the optical current measurement system, it is very hard to precisely measure small currents due to the problem of system stabilization.

3. Experimental Apparatus

Figure 1 shows a schematic diagram of the current measuring system devised by us. Here, the Faraday sensor is separated from the main part of the system with a longer fiber cable of 10 m. First, a polarized diode laser (λ: 1,330 nm) is modulated using a Faraday

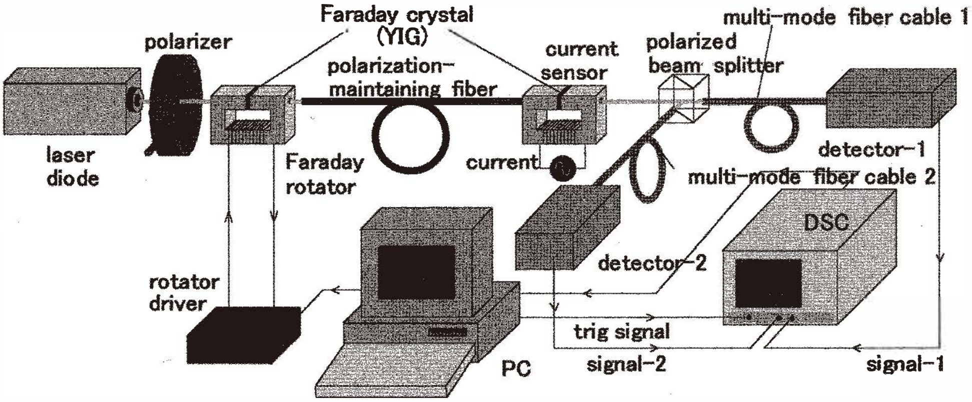


Fig. 1. Optical current measurement system

rotator controlled by a rotator driver. Here, the modulation frequency is 1.0 kHz. The modulated laser beam is transferred to the current sensor (Faraday crystal: YIG) after passing through the polarization-maintaining fiber cable as shown in Fig. 1. The polarized light maintaining the rotation angle, which is proportional to the current flowing in the Faraday sensor, is transferred to a polarized beam splitter. Two beams divided by the polarized beam splitter are converted to electrical signals using both detector-1 and detector-2 after passing through each multimode fiber cable. Here, one of the polarized laser beams, whose rotation angle is 0°, is inserted into the first phase axis of the polarization-maintaining fiber cable and another whose plane is rotated 90° using the Faraday rotator is inserted into the slow phase axis.

Finally, after processing the rotation angle of the laser beam recorded with a personal computer, the value of the current can be estimated.

4. Algorithm

In the optical current measurement system shown in Fig. 1, these optical elements are analyzed using John's matrix as follows;

$$\begin{bmatrix} E_{x2} \\ E_{y2} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\Delta\phi & -\sin\Delta\phi \\ \sin\Delta\phi & \cos\Delta\phi \end{bmatrix} \frac{1}{2} \begin{bmatrix} (e^{-\alpha_f l/2} + e^{-\alpha_s l/2} e^{-j\Delta\theta}) & (e^{-\alpha_f l/2} - e^{-\alpha_s l/2} e^{-j\Delta\theta}) \\ (e^{-\alpha_f l/2} - e^{-\alpha_s l/2} e^{-j\Delta\theta}) & (e^{-\alpha_f l/2} + e^{-\alpha_s l/2} e^{-j\Delta\theta}) \end{bmatrix}$$

$$\times \begin{bmatrix} \cos\phi_m & -\sin\phi_m \\ \sin\phi_m & \cos\phi_m \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} E_{x1} \\ E_{y1} \end{bmatrix}, \qquad (2)$$

where the left-hand term indicates the electric field waves of E_{x2} and E_{y2} corresponding to the output light intensity of the polarized beam splitter. Contrary to this, the first matrix of the right-hand term is the polarized beam splitter, the second is the current sensor consisting of the Faraday crystal, the third is the polarization-maintaining fiber cable, the fourth is the Faraday rotator, the fifth is the polarizer, and the last is the electric field wave of E_{x1} and E_{y1} corresponding to the incident light intensity, respectively. In the third matrix, it is assumed that the phase difference produced between the fast axis and the slow axis of the longer fiber cable is taken account of as that produced only in the slow axis because the rotation angle of the fast axis is 0°. In eq. (2), $\Delta\phi$ is the rotation angle of the laser beam in the Faraday current sensor, α_f and α_s are the attenuation coefficients in the fast and slow phase axes of the polarization-maintaining fiber, l is the length of the fiber cable, $\Delta\theta$ is the retardation angle between the two axes of the fiber cable, and ϕ_m is the rotation angle of the laser beam modulated by the Faraday rotator. Intensities of P- and S-polarized light, I_P and I_S, obtained with two photodetectors can be calculated using eq. (2) as follows;

$$I_P = \frac{I_0}{4}\Gamma_1(I)e^{-\beta_2 L}\{\left(e^{-\alpha_f l} + e^{-\alpha_s l}\right)(1 - \sin 2\Delta\phi \sin 2\phi_m) + 2e^{-\alpha_f l}e^{-\alpha_s l}\cos\Delta\theta\cos 2\Delta\phi\cos 2\phi_m$$

$$+\left(e^{-\alpha_f l} + e^{-\alpha_s l}\right)(\sin 2\phi_m - \sin 2\Delta\phi)\} \tag{3}$$

$$I_S = \frac{I_0}{4}\Gamma_2(I)e^{-\beta_2 L'}\{\left(e^{-\alpha_f l} + e^{-\alpha_s l}\right)(1 + \sin 2\Delta\phi \sin 2\phi_m) - 2e^{-\alpha_f l}e^{-\alpha_s l}\cos\Delta\theta\cos 2\Delta\phi\cos 2\phi_m$$

$$+\left(e^{-\alpha_f l} - e^{-\alpha_s l}\right)(\sin 2\phi_m - \sin 2\Delta\phi)\}, \tag{4}$$

where I_0 is the intensity of the incident light, and $\Gamma_1(I)$ and $\Gamma_2(I)$ indicate the output intensities of the two photodetectors. β_1 and β_2 are the attenuation coefficients of the multimode fiber cables, and L and L' are the lengths of the fiber cables. In this experiment, ϕ_m is already fixed at ±45° with the Faraday rotator.

Figure 2 shows a typical relationship between the output intensity of the polarizer and the rotation angle produced by the Faraday sensor. In the figure, it is defined that when the modulation angle ϕ_m is set to +45°, the P-polarized light is defined as I_P^+ and the S-polarized light is defined as I_S^+. Contrary to this, it is also defined that when the modulation angle ϕ_m is set to –45°, the P-polarized light is defined as I_P^- and the S-polarized light is defined as I_S^-, respectively. The light intensities of I_P^+, I_S^+, I_P^- and I_S^- are defined by the following equations.

$$I_P^+ = \frac{1}{2}I_0 e^{-\beta_1 L}e^{-\alpha_f l}\Gamma_1(I)(1 - \sin 2\Delta\phi)$$

$$I_S^+ = \frac{1}{2}I_0 e^{-\beta_2 L'}e^{-\alpha_f l}\Gamma_2(I)(1 + \sin 2\Delta\phi)$$

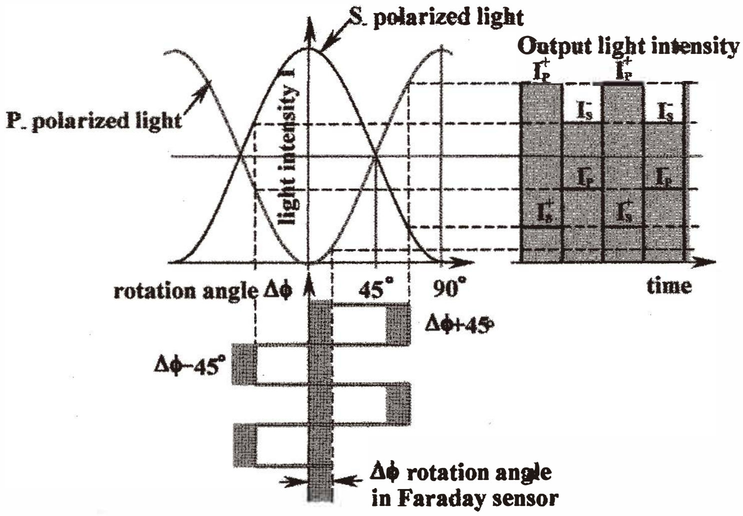


Fig. 2. Characteristic curve of output light intensity against rotation angle produced by Faraday sensor.

$$I_{\mathrm{P}}^{-} = \frac{1}{2} I_0 e^{-\beta_1 L} e^{-\alpha_s l} \Gamma_1(I)(1 + \sin 2\Delta\phi)$$

$$I_{\mathrm{S}}^{-} = \frac{1}{2} I_0 e^{-\beta_2 L'} e^{-\alpha_s l} \Gamma_2(I)(1 - \sin 2\Delta\phi) \tag{5}$$

From eq. (5), it can be seen that the difference in retardation angle $\Delta\theta$ between the two axes of the polarization-maintaining fiber is theoretically eliminated. By dividing I_{P}^{+} by I_{S}^{+} and I_{P}^{-} by I_{S}^{-}, α_{f} and α_{s} which are the attenuation coefficients in the fast and slow phase axes of the polarization-maintaining fiber can be theoretically eliminated. Furthermore, the characteristic difference between the two photodetectors $\Gamma_1(I)$ and $\Gamma_2(I)$ and the intensity of incident light I_0 is also eliminated. Finally, the rotation angle $\Delta\phi$ which is proportional to the current is derived by the following equation.

$$\Delta\phi = \frac{1}{2} \sin^{-1}\left[\frac{-(I_P^+ I_S^- + I_P^- I_S^+) + 2\sqrt{I_P^+ I_S^- I_P^- I_S^+}}{(I_P^+ I_S^- - I_P^- I_S^+)} \right] \tag{6}$$

By precisely measuring the light intensities of I_{P}^{+}, I_{S}^{+} , I_{P}^{-} and I_{S}^{+}, the rotation angle $\Delta\phi$ can be obtained after processing the four values recorded with a personal computer. From this algorithm, we theoretically achieved the system stabilization for the present optical current measurement system.

5. Experimental Results

Generally, it is well known that the stabilization of optical current measurement systems is affected by (1) the intensity fluctuation of incident light, (2) the birefringence of fiber cable, (3) the Faraday rotator, (4) the polarized beam splitter, (5) the light detector and (6) other optical elements. We have already succeeded in eliminating the birefringence produced due to factors (3), (4) and (6). However, some problems such as a frequency fluctuation of the light source and birefringence of the fiber cable still remain without solutions. From this, the following four categories have been adopted for the clarification of these problems.

(a): In the case of a Faraday rotator, a polarized beam splitter and a polarization-maintaining fiber being removed from the system shown in Fig. 1.

(b): In the case of a Faraday rotator being added to (a).

(c): In the case of only a polarization-maintaining fiber cable being removed from the system shown in Fig. 1

(d): In the case of all optical elements being used as shown in Fig. 1.

5.1 *System stabilization with both intensity and frequency fluctuations of the incident light*

Figure 3 shows the relationship between the amplitude fluctuation of output signals and the frequency fluctuation of incident light. Here, the modulation frequency and the intensity fluctuation of incident light are fixed at 1.0 kHz and 12%, respectively. From the figure, it can be seen that when the frequency of incident light is changed from 0 to 1.0 kHz, the intensity fluctuation of incident light decreases by less than 10% in the frequency range from 0 to 1.0 kHz, except for that obtained in the case of (a) and (b). In the case of (a), it is evident that the intensity fluctuation of incident light cannot be eliminated because no

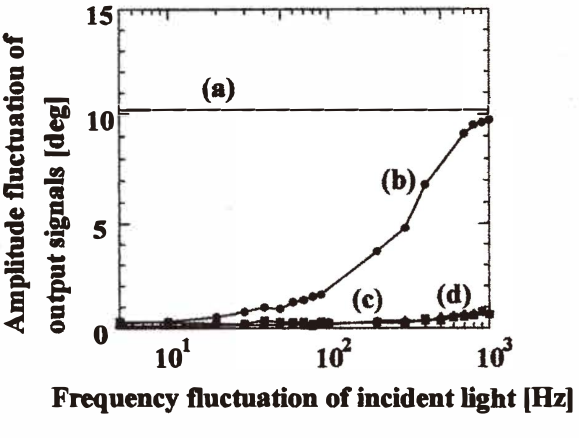


Fig. 3. Relationship between amplitude fluctuation of output signals and frequency fluctuation of incident light.

element exists in the system to increase the ratio of S/N. Contrary to this, in the case of (b) it is possible to eliminate the intensity fluctuation of incident light at low frequencies, but this becomes impossible as the modulation frequency approaches to 1.0 kHz.

5.2 *System stabilization with the characteristic intensity differences between two photodetectors*

For investigating the effect of characteristic intensity differences between two photodetectors, the output intensity function of photodetector-2 $\Gamma_2(I)$ was changed from 100% to 20% while that of photodetector-1 $\Gamma_1(I)$ was fixed at 100%. Figure 4 shows a typical characteristic curve for the measured rotation angle of output light $\Delta\phi$ against the standard rotation angle as a function of output intensity of phtodetector-2. Here, the half wave plate is used as a standardized rotation angle instead of a Faraday sensor.

From Fig. 4, it is evident that, using the azimuth angle modulation method, the new type optical current sensor is useful for precisely measuring the rotation angle $\Delta\phi$ which is proportional to the current supplied by means of the Faraday sensor, even though the two characteristic functions of $\Gamma_1(I)$ and $\Gamma_2(I)$ are not equal.

5.3 *Measurement of AC and DC currents*

Figure 5 shows a typical rotation angle of the polarized plane of incident light against AC or DC magnetic field, corresponding directly to AC or DC current, respectively. In the figure, Fig. 5(a) shows an experimental result obtained with AC magnetic field application to the Faraday sensor, while Fig. 5(b) shows that obtained with DC magnetic field

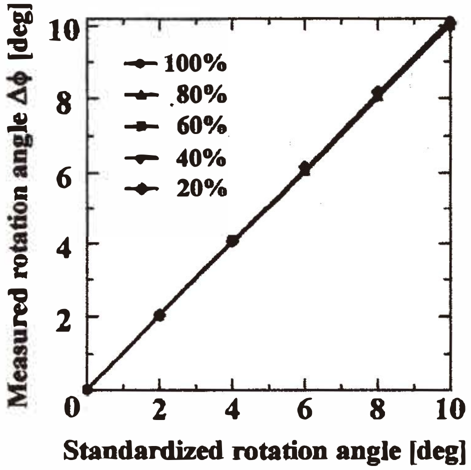


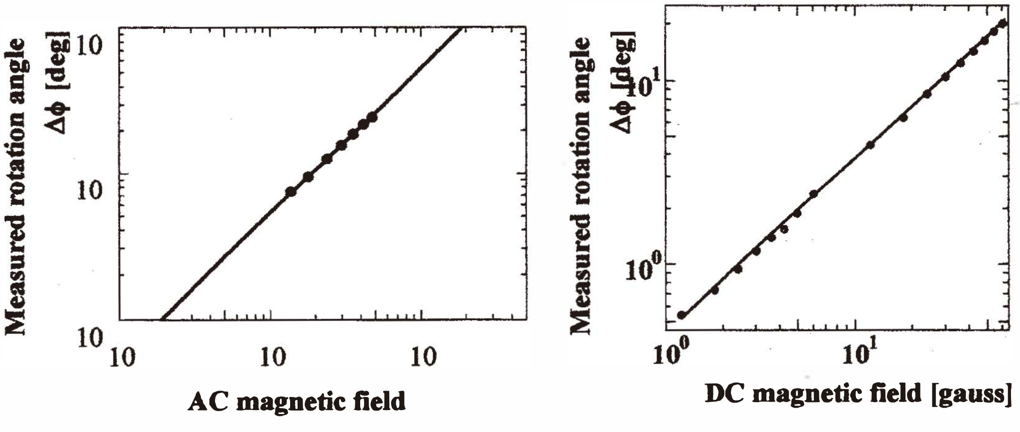
Fig. 4. Measured rotation angle $\Delta\phi$ against standardized rotation angle as a function of amplitude coefficient of photo-detector-2 in the case of (d).

application. Here, circles indicate the experimental results while a solid line indicates the theoretical. In Fig. 5(a), the vertical axis indicates the measured rotation angle and the horizontal axis indicates the AC magnetic field, while in Fig. 5(b) the vertical axis indicates the measured rotation angle and the horizontal axis indicates the DC magnetic field.

In Fig. 5(a) obtained with the AC magnetic field application to the Faraday sensor, it can be seen that the characteristic curve is a straight line in the magnetic field range of 0 to 50 Gauss. Contrary to this, in Fig. 5(b) obtained with the DC magnetic field application, the characteristic curve is a straight line in the DC magnetic field range of 0 to 60 Gauss.

6. Conclusions

In this work, it was experimentally found that the intensity fluctuation of the incident light, the birefringence in the optical fiber cable and also the characteristic intensity differences between the two photodetectors can be eliminated using both the azimuth angle modulation and the P- and S- polarized light division methods. Furthermore, it is theoretically proved by using John's matrix that stabilization of the present optical current system can be achieved. Finally, it is proposed that this new type current measurement system is useful for measuring not only AC but also DC currents flowing in the high potential area. However, more research is required to increase the sensitivity of the current measurement system.



(a) AC current

(b) DC current

Fig. 5. Relationship between the rotation angle in the Faraday sensor and the magnetic field, corresponding to AC and DC currents.

References

1 S. Saito, Y. Fujii, J. Hamasaki and K. Yokoyama: Inst. of Inds. Scie; Univ. of Tokyo **28** (1980) p. 225.
2 T. W. MacDougall, D. R. Lutz and R. A. Wandmacher: IEEE Trans. P.D. 7 (1992) p. 848.
3 R. L. Heredero, R. F. de Caleya, H. Guerrero, P. L. Santos, M. C. Acero and J. Estave: Appl. Opt. **38** (1996) 5298.
4 M. Higaki: IEE, Japan **116**-B (1996) 80.
5 K. Kurosawa, S. Yoshida, K. Sakamoto, I. Masuda and T. Yamashita: IEE Japan **116**-B (1996) 94.
6 Z. P. Wang, W. M. Sun, Z. J. Huang, C. Kang, S. L. Ruan, Y. H. Luo, A.W. Palmer and K. T. V. Grattan: Appl. Opt. **37** (1998) 7293.
7 G. W. Day and A. H. Rose: SPIE 985, Fiber Optics and Laser VI (1988) p. 138.
8 R. L. Patterson, A. H. Rose, D.Tang and G. W. Day: IEEE AES System Magazine **5** (1990) 10.
6 S. Muto, N. Seki, T.Suzuki and T. Tsukamoto: J. J.Appl. Phys. **31** (1992) L436.
7 J. L. Cruz, M. V. Andres and M. A. Herznandez: Appl. Opt. **35** (1996) 922.
8 A. H. Rose, D.Tang and G. W. Day: J. Lightwave Tech. **14** (1996) 2492.
9 T. Yoshino, M. Gojyuki, Y. Takahashi and T. Shimoyama: Appl. Opt. **36** (1997) 5566.
10 K. Kurosawa: IEE Japan **117**-B (1997) 354.
11 H. Lin, W.W. Lin and M. H. Chen: Appl. Opt. **38** (1999) 2760.
12 K. Hidaka and Y. Murooka: IEE Proc. **132** pt-A (1985)p. 139.
13 Y. Murooka and T. Nakano: Rev. Sci. Instrum. **63** (1992) 5582.
14 Y. Murooka and T. Nakano: Rev. Sci. Instrum. **65** (1994) 2351.
15 T. Hirose, T. Takada and Y. Murooka: ISH99, 1, 160.S6, London, August (1999).
16 T. Hirose, T. Takada and Y. Murooka: 10th ACED, F-623, Kyoto, Japan, November (2000).

About the Authors

Takashi Hirose was born in Tokyo, Japan on January 22, 1976. He received B.S. and M.S. degrees in engineering from the Musashi Institute of Technology, Japan, in 1998 and 2000. He studied an optical current measurement system using an azimuth angle modulation method from 1997 to 2000 at the Musashi Institute of Technology, Japan. He currently works at JGC Information System Co., Ltd., Japan. He can be reached at the Musashi Institute of Technology, 1-28-1 Tamazutsumi, Setagaya-ku, Tokyo 158-8557, Japan. Fax: 81 (Japan) 03-5707-2156, E-mail: hirose@dept1.jsys.co.jp.

Tatsuo Takada was born on August 8, 1939 in Japan. He received his B.E. degree in electrical engineering from the Musashi Institute of Technology, Japan, in 1963, and his M.E. and D.E. degrees from the University of Tohoku, Japan, in 1966 and 1975. He was appointed as a lecturer at the Musashi Institute of Technology in 1967. He became an associate professor at the same university in 1974 and a professor in 1987. He was a visiting scientist at MIT (USA) from 1981 to 1983. He has undertaken several research projects on the space charge effect in solid dielectric materials, surface charges accumulated on thin-film surfaces, and electric field measurement in liquid materials. He received excellent paper awards form the IEE of Japan in 1974, 1981 and 1990. In 1999, he received the Whitehead Memorial Award from the CEIDP of IEEE. He is a member of IEEE fellowship. He can be reached at the Musashi Institute of Technology, 1-28-1 Tamazutsumi, Setagaya-ku, Tokyo 158-8557, Japan. Fax: 81 (Japan) 03-5707-2156, E-mail: takada@me-musashi-tech.ac.jp.

Yoshihiro Murooka was born on February 16, 1931 in Japan. He received his M.S. degree from the University of Tohoku in 1958 and was appointed as a research associate at the National Defense Academy in 1958. He received his D.E. degree from the University of Tohoku in 1963 and his Ph.D. degree from the University of Liverpool (U.K.) in 1968. In 1969, Dr. Murooka was appointed as a professor at the National Defense Academy. He retired from the National Defense Academy in 1997 and was appointed as an emeritus professor at the academy that same year. He was also appointed as a professor at the Musashi Institute of Technology, Japan, in 1997. His research work from 1958 to 1997 includes: (1) Nanosecond surface discharge phenomena using a dust figure technique, (2) electronic phenomena in liquids using a bubble chamber devised to optically observe and detect high energy particles, and (3) long gap discharge in air using an optical novel technique. His honors include: Proportion Medals from IEE Japan in 1985 and 1998. Duddell Premium from IEE England in 1986, 100 year Anniversary Competition Medal from IEE Japan in 1988, Scientific Achievement Medal from the Japanese Government in 1989. His books include: (1) High Voltage Engineering, (2) Liquid Electronics, (3) Corona Phenomena, (4) I Am An Electron, and (5) What Is Electricity? He is a member of IEE Japan. He can be reached at the Shibaura Institute of Technology, 3-9-14 Shibaura, Minato-ku, Tokyo 108-8548, Japan. Fax: 81 (Japan) 03-5427-7806, E-mail: i018004@sic.shibaura-it.ac.jp.