Analysis on High Resolution Method for CCD Image Sensor Using Swing and Wobbling Imaging

スウィングとウォーブリング撮像を用いたCCDイメージセンサの高解像度化方式についての解析

Nozomu Harada† (member) and Okio Yoshida††

Abstract High resolution solid-state image sensors are strongly required for many imaging systems. Double resolution enhancement without increasing CCD pixel density was achieved by CCD-chip swing operation. Furthermore, a wobbling operation enlarging a pixel aperture is capable to suppress effectively a field flicker. We analytically derive that a triangular wave swing and wobbling operation is superior to a rectangular wave mode for higher resolution imaging in considering aliasing. Also, an optimum condition for the triangular wave swing and wobbling operation is derived.

Key words : Solid state image sensor, Nyquist frequency, Resolution, Aliasing, Fourier transform

1. Introduction

Resolution is one of the most important aspects of imaging system performance. Resolution improvement has been strongly and continuously required for solid-state image sensors. The number of pixels of the current CCD image sensors for digital-still cameras is in the range of one to three millions\(^2\). A 35 mm color film has color dots of about eight millions. Consequently, achieving picture quality equal to that of the 35 mm color film is one of the targets for the CCD image sensors. Next generation super high definition TV systems will requires eight million pixels for image sensors. The resolution improvement is required for CCDs, not only for TV systems but also in many imaging applications including a medical field, an astronomical field, and measurement systems, etc.

The resolution improvement has been achieved simply by an increase of pixel density and by an expansion of image area\(^2\). In the case of single chip color sensors, the enhancement methods by smart signal processing taking various color pixel arrangement have been studied\(^1,2\). In answering the high-resolution requirement, the authors successfully developed a Swing CCD to realize double resolution enhancement by using a CCD chip shifting operation\(^3-8\). Though a swing operation using an incident image shifting instead of the CCD chip shifting is able to give the same resolution enhancement effect\(^9,10\), the swing CCD has advantages in that a double resolution improvement is achieved without degradations of dynamic range and sensitivity, and without efforts to increase the CCD pixel density.

Previously, we analyzed the swing operation rather broadly. Here, we analyze the Modulation Transfer Function (MTF) for higher resolution swing operation in details. Also, by introducing an aliasing rate, we show a quantitative evaluation of the aliasing phenomena. Additionally, a suitable operation condition for higher resolution Swing CCD is proposed by using the analytical results.

2. Swing Operation Principle

In a CCD image sensor, pixels are periodically arranged in two dimensions. Each pixel has a photosensing area defining an aperture shape. As shown in Fig. 1, a pixel pattern function \(g(x, y)\) is written as a convolution of a pixel sampling function \(s(x, y)\) with a pixel aperture function \(f(x, y)\):

\[
g(x, y) = s(x, y) * * f(x, y)
\]

When pixels are arranged in a rectangular pattern with
pixel numbers of \((2N) \times (2M)\) as shown in this figure, \(s(x, y)\) is denoted by two-dimensional delta function:

\[
s(x, y) = \sum_{n=-N}^{N} \sum_{m=-M}^{M} \delta(x - np_x) \delta(y - mp_y) \tag{3}
\]

where \(n\) and \(m\) are integers, \(p_x\) and \(p_y\) are pixel pitches in \(x\)-and \(y\)-directions, respectively. \(G(u, v), S(u, v)\) and \(F(u, v)\) show Fourier transforms of \(g(x, y), s(x, y)\) and \(f(x, y)\), respectively. \(G(u, v)\) is given as follows:

\[
G(u, v) = \int_{-\infty}^{\infty} g(x, y) \exp[-j2\pi(xu + yv)] \, dx \, dy = S(u, v)F(u, v) \tag{4}
\]

where \(u\) and \(v\) are special frequencies in \(x\)-and \(y\)-directions, respectively. It can be seen that the Fourier transform of the convolution is simply given by the product of the individual transforms of \(s(x, y)\) and \(f(x, y)\). This is an extremely useful result because the analytical studying of individual \(s(x, y)\) and \(f(x, y)\) leads to understandings of the resolution of the image sensor. Here, \(S(u, v)\) shows a rectangular reciprocal lattice pattern. A range of the reproducible image exists in the first Brillouin zone. The boundary of the zone means a Nyquist frequency, that is a resolution limit.

The Nyquist frequencies \(F_{nx}\) and \(F_{ny}\) in \(x\)-and \(y\)-directions are given by

\[
F_{nx} = \frac{1}{2} p_x, \quad F_{ny} = \frac{1}{2} p_y. \tag{5}
\]

When \(u\) and \(v\) are rewritten to the normalized frequencies \(u^* = u/F_{nx}\) and \(v^* = v/F_{ny}\), respectively. An MTF (Modulation Transfer Function) is given by sinc function:

\[
MTF = \left| \frac{F(u^*, v^*)}{F(0, 0)} \right| = \frac{\sin \left( \frac{\pi}{2} a_x u^* \right) \sin \left( \frac{\pi}{2} a_y v^* \right)}{\frac{\pi}{2} a_x u^* \cdot \frac{\pi}{2} a_y v^*} = \sin \left( \frac{\pi}{2} a_x u^* \right) \cdot \sin \left( \frac{\pi}{2} a_y v^* \right), \tag{7}
\]

where, we put aperture ratios in \(x\)-and \(y\)-directions into \(a_x(=a/p_x)\) and \(a_y(=a/p_y)\), respectively.

Fig. 2 shows the swing operation principle with a rectangular wave CCD chip shifting. The CCD chip is an interline-transfer CCD, in which a unit pixel is composed of a photosensing area with a rectangular aperture shape and a vertical CCD register for signal charge read-out. The vertical CCD register is optically shielded. One frame picture is formed by two field pictures of field A and B. Storage signal charges during the field A period are transferred to the vertical CCD register during a vertical blanking period. This signal charge transfer is simultaneously operated in all pixels. At the same time or just after the signal charge transfer, the CCD chip is shifted horizontally to a new position at a half pixel distance. Then, signal charge storage for the field B starts at the new position. Thus, obtained time-shared images with horizontally interlaced signals are arranged on a display monitor to produce images with double enhanced resolution. As resultant, two pixel apertures are formed in the unit pixel of the conventional CCD by using the swing CCD operation, the horizontal Nyquist frequency is doubly enhanced for the swing operation:

\[
F_{nx} = \frac{1}{p_x}. \tag{8}
\]
The MTF for the swing operation is shown in a same expression as in Eq. (7) for conventional CCD without the swing operation. In addition to the resolution limit expansion, a low MTF at an enhanced Nyquist frequency \( u^* = 2 \) leads to a reduction of "aliasing phenomena". When fine repeated pattern is imaged, the aliasing causes a deformed signal called as "moire", or "beat pattern" in the reproduced picture. An aliasing signal suppression is important in obtaining a high resolution picture because the aliasing near the Nyquist frequency leads to resolution limit reduction. The aliasing in low frequencies leads substantially to quality degradation of an entire image. Therefore, a MTF design considering the aliasing suppression is required for a higher resolution Swing CCD.

3. Triangular Wave Swing Operation

Instead of the rectangular swing operation so far analyzed, a triangular swing operation is analyzed in a standpoint of aliasing suppression.

Fig. 3 shows the pixel aperture shifting and the pixel sensitivity shape in the triangular wave swing operation. The CCD chip is horizontally shifted right and left in triangular wave. In each field, the center of pixel aperture starts from a swing center \( x = 0 \) and reaches to \( x = \pm \frac{p_x}{2} \), and returns to the swing center. In this case, an averaged pixel center through the field period exists at \( x = \pm \frac{p_x}{4} \), being the same position for the rectangular wave swing operation. In the condition of \( a < \frac{p_x}{2} \), two pixel apertures formed are not overlapped with each other. Considering one way direction moving of the pixel, the sensitivity shape becomes a trapezoid. When a storage signal charge during one field period is \( Q_x \), the sensitivity at \( a/2 < x < (p_x - a/2) \) is given as the following:

\[
 s = \frac{Q_x}{p_x}.
\]  

The pixel sensitivity shape through the field time also become trapezoid because the shapes of both ways are the same. Therefore, the sensitivity at the flat portion through the two way is a double of that of the one way moving; \( 2Q/p_x \). The sensitivity shape function \( f(x) \) is shown by a convolution of rectangular functions \(^{13}\)

\[
f(x) = \text{rect} \left( \frac{2x}{p_x} \right) \ast \text{rect} \left( \frac{x}{a} \right). \tag{10}
\]

When the Fourier transform of \( f(x) \) is \( F(u^*) \), using pixel aperture ratio \( a \) and normalized frequency \( u^* \), the MTF in the \( x \) direction is expressed as follows:

\[
\text{MTF} = \left| \frac{F(u^*)}{F(0)} \right| = \frac{\sin(\pi a u) \cdot \sin \left( \frac{\pi}{2} a u^* \right)}{\sin \left( \frac{\pi}{2} a u^* \right) \cdot \sin \left( \frac{\pi}{4} u^* \right)} = \frac{\sin(\pi a u)}{\sin \left( \frac{\pi}{2} a u^* \right) \cdot \sin \left( \frac{\pi}{4} u^* \right)}. \tag{11}
\]

As seen in this equation, the triangular wave swing operation is equal to a MTF of the rectangular wave swing operation modulated by a low pass filter expressed with \( \sin(\pi a u) / \sin(\pi a u^*) \) in the direction.

Fig. 4 illustrates comparisons of MTFs for the rectangular, the triangular wave swing operation and the conventional operation without swing in the case of \( a = 1 \). Nyquist frequencies are located at \( u^* = 1 \) for the conventional operation without swing and at \( u^* = 2 \) for the rectangular and the triangular swing operation, respectively. The conventional operation has a high MTF at the Nyquist frequency \( u^* = 1 \), resulting a high aliasing at around Nyquist frequency. An optical low-pass filter is generally used for the aliasing reduction. An MTF using the optical low-pass filter is usually denoted as

\[
\text{MTF} = \left| \sin \left( \frac{\pi}{2} a u^* \right) \cdot \cos \left( \frac{\pi}{2} u^* \right) \right|. \tag{12}
\]

Where the MTF at \( u^* = 1 \) becomes zero. Resolution is generally evaluated to be higher when the MTF is higher in a range below the Nyquist frequency and the aliasing is lower. As shown in this figure, inside the
Nyquist frequency, the MTF of the rectangular wave swing operation is higher than that of the triangular wave mode. The MTF of the triangular wave swing operation has a lower value compared with that of the rectangular wave swing operation outside of the Nyquist frequency. This means the triangular swing operation can reduce the aliasing. From a viewpoint of resolution evaluation, therefore, it is necessary to consider an effect of aliasing in the Nyquist frequency for a quantitative evaluation of resolution. The aliasing appears in the lower frequency region by return of high spatial frequency components of the MTF with mirror-reflectance characteristics at integer multiplication of the Nyquist frequency. For this resolution evaluation, we have newly introduced a ratio of the aliasing amplitude to the MTF inside Nyquist frequency, referring to this ratio as the aliasing rate. The \( N \)th aliasing rate \( AN(u^*) \) for the triangular wave swing operation is given by

\[
AN(u^*) = \frac{\sin\left(\frac{\pi}{2} \alpha u^* (2N+1-u^*)\right)}{\sin\left(\frac{\pi}{2} \alpha u^*\right)}
\]

\[
= \frac{\sin\left(\frac{\pi}{4} \left(2N+1-u^*\right)\right)}{\sin\left(\frac{\pi}{4} u^*\right)}
\]  

\( (N: \text{odd}) \),

\[
= \frac{\sin\left(\frac{\pi}{4} \left(N+1-u^*\right)\right)}{\sin\left(\frac{\pi}{4} u^*\right)}
\]

\( (N: \text{even}) \).

Where \( N \) is integers expressing the \( N \)th Nyquist region.

Fig. 5 shows comparisons of the first aliasing rate \( A1(u^*) \) for the rectangular wave and the triangular wave and the conventional mode without swing operation when \( \alpha_r \), an \( x \)-direction aperture ratio, is unity. As shown in this figure, the triangular wave swing operation gives the lowest aliasing rate among these three operation modes.

Fig. 6 shows the first aliasing rate characteristics.
when \( \alpha_x \) is varied. This figure shows that the aliasing rate for each \( \alpha_x \) is pinned to zero. This pinning at \( u^* = 0 \) due to the additional low-pass filter effect of \(|\text{sinc}(\pi u^*/4)|\), leading to the aliasing reduction at low frequency region. This pinning occurs at all of the \( N \)th aliasings. In addition, a double pinning at \( u^* = 0 \) and \( u^* = 2 \) is obtained when \( \alpha_x \) is unity.

Fig. 7 shows a comparison of the first aliasing rate for the rectangular and the triangular wave swing operation when \( \alpha_x \) is varied. As shown in this figure, the triangular wave swing operation is superior to the rectangular wave mode. In particular, the aliasing at low frequency is remarkably improved when \( \alpha_x \) is small.

We analytically derived the superiority of the triangular wave swing operation compared with the rectangular wave operation and shown that the triangular swing operation has a feature such that the aliasing signals at \( u^* = 0 \) are pinned to zero.

4. Swing Operation with Wobbling

An MTF control is realized by a CCD-chip wobbling operation in which wobbling or a vibration is superimposed at swung sites\(^8\). The MTF is controlled basically due to a pixel aperture expansion using the wobbling. In the swing operation, the image at each field has an aliasing with the Nyquist frequency of \( u^* = 1 \). This aliasing is compensated by combining two field images. When an aliasing difference exists between these two successive field images, a field flicker appears occasionally in a fine pattern image or in an image of an object with abrupt edge having high frequency components. The swing operation with the wobbling overlaps pixel sensitivities between two field times, and reduces successively the field flicker in reproduced pictures.

Fig. 8 shows comparisons of pixel sensitivity shapes for the rectangular and the triangular wave wobbling operations. If wobbling amplitudes of rectangular and triangular wave wobbling operation are \( 2L_{wr} \) and \( 2L_{wt} \), respectively, an overlapping condition of pixel sensitivities of the two fields is described by a similar expression for each wobbling operation:

\[
L_{wr} + \frac{a}{2} \leq \frac{p_x}{2} \quad \text{(rectangular),}
\]

\[
L_{wt} + \frac{a}{2} \leq \frac{p_x}{4} \quad \text{(triangular).}
\]

In the rectangular wobbling operation, a pixel sensitivity shape function \( f(x) \) is obtained by addition of rectangular function \( f_1(x) \) and \( f_2(x) \) located at \( x = \pm L_{wr} \) for
the field swing center \( x=0 \):

\[
f(x) = f_1(x) + f_2(x) = \frac{Qe}{2a} \left( \text{rect} \left( \frac{x-L_{wt}}{a} \right) + \text{rect} \left( \frac{x}{a} \right) \right).
\]

The sensitivity function \( f(x) \) shows a convex shape. Then, its Fourier transform is given by

\[
F(u) = \frac{Qe}{a} \left[ \text{sinc}(\pi au) \exp(-j2\pi L_{wt}u) + \text{sinc}(\pi au) \exp(j2\pi L_{wt}u) \right]
\]

\[
= \frac{Qe}{a} \text{sinc}(\pi au) \cos(2\pi L_{wt}u). \quad (16)
\]

Using the aperture ratio \( \alpha_c = a/p_x \), a wobbling rate \( \beta_x = L_{wt}/p_x \) and the normalized frequency \( u^* = 2u/p_x \), the MTF for the rectangular wobbling operation is given by

\[
\text{MTF} = \left| \frac{F(u^*)}{F(0)} \right| = \left| \text{sinc} \left( \frac{\pi}{2} \alpha_c u^* \right) \cos(\pi \beta_x u^*) \right|. \quad (17)
\]

The MTFs for various overlapping conditions for \( L_{wt} + a/2 > p_x/4 \) are also described by Eq. (17).

Next, considering the triangular wobbling, a pixel sensitivity shape function \( f(x) \) is described by addition of the trapezoid shape functions of \( f_1(x) \) and \( f_2(x) \)

\[
f(x) = f_1(x) + f_2(x) = \frac{Qe}{2a} \left[ \text{rect} \left( \frac{x-L_{wt}}{a} \right) \text{rect} \left( \frac{x}{a} \right) \right]
\]

\[
+ \text{rect} \left( \frac{x}{a} \right) \text{rect} \left( \frac{x+L_{wt}}{2a} \right). \quad (18)
\]

Then, its Fourier transform \( F(u^*) \) is given by

\[
F(u^*) = \frac{Qe}{a} \text{sinc}(\pi L_{wt}u) \text{sinc}(\pi au) \cos(\pi L_{wt}u)
\]

\[
= \frac{Qe}{a} \text{sinc}(\pi au) \frac{\sin(\pi L_{wt}u)}{\pi L_{wt}} \cos(\pi L_{wt}u)
\]

\[
= 2\frac{Qe}{a} \text{sinc}(\pi au) \frac{\sin(2\pi L_{wt}u)}{2\pi L_{wt}}
\]

\[
= 2\frac{Qe}{a} \text{sinc}(\pi au) \sin(2\pi L_{wt}u)
\]

\[
= 2\frac{Qe}{a} \text{sinc} \left( \frac{\pi}{2} \alpha_c u^* \right) \sin(\pi \beta_x u^*), \quad (19)
\]

where \( \beta_x \) is \( L_{wt}/p_x \), calling a wobbling rate for the triangular wobbling. Therefore, the MTF for the triangular wobbling is given by

\[
\text{MTF} = \left| \text{sinc} \left( \frac{\pi}{2} \alpha_c u^* \right) \sin(\pi \beta_x u^*) \right|. \quad (20)
\]

The MTF for another condition of \( L_{wt} + a/2 > p_x/4 \) is also described by the Eq. (20) as far as these two pixel sensitivity shapes are trapezoids. In the Eq. (20), if \( \beta_x = 1/4 \), the MTF is the same as that in Eq. (11) for the triangular wave swing operation. The MTFs at \( \alpha_c = 0.5 \) and \( \beta_x = \alpha_c/2 \) are also the same as those in the triangular wave wobbling. This shows that the triangular wave wobbling operation varying the wobble amplitude has the similar effect with the triangular wave swing operation.

**Fig. 9** shows MTF characteristics of the triangular wobbling operation in the case of \( \alpha_c = 0.5 \) when \( \beta_x \) is varied. As shown in this figure, the MTF becomes zero at a frequency less than the Nyquist frequency of \( u^* = 2 \) in the case of \( \beta_x > 0.5 \). This means that the resolution limit becomes less than \( u^* = 2 \). Therefore, \( \beta_x \) should be set to less than 0.5.

**Fig. 10** shows the first aliasing rate characteristic in the case of \( \alpha_c = 0.5 \) when \( \beta_x \) is varied at \( \beta_x < 0.5 \). As shown in the figure, the aliasing at \( u^* = 0 \) is pinned to zero for the condition of \( \alpha_c = 0.5 \). In this case, the more \( \beta_x \) increases at \( \beta_x < 0.25 \), the less the aliasing rate monotonously decreases. In the case of \( 0.25 < \beta_x < 0.5 \), the aliasing rate at low frequency region is further suppressed low with the pinning effect at \( u^* = 0 \). The aliasing rate in the condition of \( \beta_x = 0.25 \) coincides with that of \( \beta_x = 0.5 \). This means that the MTF for \( \beta_x = 0.5 \) coincides with that of \( \beta_x = 0.25 \) when the MTF for \( \beta_x = 0.25 \) is operated as to be zero at \( u^* = 2 \).

An optimum condition of \( \alpha_c \) and \( \beta_x \) is shown in **Fig. 11**. The Equation (15) should be satisfied for the sensitivity overlap between pixels of the two fields. The \( \beta_x \).
should be less than 0.5, preventing resolution limit frequency from decreasing to less than \( u^* = 2 \). The aliasing rate for \( 0.25 < \beta_x < 0.5 \) is able to be reduced to a smaller value than that for \( \beta_x < 0.25 \). The similar suppression effect of the aliasing rate can be obtained by controlling of \( \beta_x \) instead of \( \beta_x \). A condition for smaller aliasing rate is \( 0.5 < \beta_x < 1.0 \). Therefore, the region bounded by \( 0.25 < \beta_x < 0.5 \) and \( 0.5 < \alpha_x < 1.0 \) satisfies analytically the condition for the smaller aliasing rate imaging. In this region, the condition of \( \alpha_x = 1.0 \) or \( \beta_x = 0.5 \) gives the double zero pinning at \( u^* = 0 \) and \( u^* = 2 \), realizing the best condition for higher resolution picture with low aliasing. The \( \alpha_x \) and the \( \beta_x \) should be practically chosen by taking accounts of pixel aperture fabricated on CCD, an imaging object, and an optical lens used, etc.

A ratio of the aliasing rates for the triangular and the rectangular wobbling, \( T(u^*) \), is obtained from Eqs. (13), (17) and (20) as

\[
T(u^*) = \left| \frac{\sin \left( \frac{\pi}{2} \beta_x (4 - u^*) \right)}{\sin \left( \frac{\pi}{2} \beta_x u^* \right)} \right| \left| \frac{\cos \left( \frac{\pi}{2} \beta_x (4 - u^*) \right)}{\cos \left( \frac{\pi}{2} \beta_x u^* \right)} \right|
\]

Fig. 10 The first aliasing rate characteristic in the case of \( \alpha_x = 0.5 \) when \( \beta_x \) is varied at \( \beta_x < 0.5 \).

Fig. 11 Optimum conditions of \( \alpha_x \) and \( \beta_x \) for the triangular wave wobbling operation.

Here, \( \beta_x \) for the rectangular wobbling should be substituted by \( \beta_x / 2 \) when the comparison is made at the same pixel center position for the rectangular wave and the triangular wave wobbling. The ratio depends on only \( \beta_x \), not on \( \alpha_x \). Fig. 12 shows the comparison of the aliasing rates for the triangular wave wobbling and the rectangular wave wobbling. As shown in the figure, the more \( \beta_x \) increases, the more the aliasing rate of the triangular wobbling is improved in the low frequency region.

As mentioned above, high resolution image with lower aliasing is obtained by using the triangular wave swing operation or the triangular wave wobbling operation. It is also derived that the triangular wave wobbling operation has the same effect with varying the pixel aperture in the case of the triangular wave swing operation.

5. Conclusions

CCD using the swing operation is capable to realize double resolution limit enhancement without pixel density increase, degradation of dynamic range and sensitivity. An wobbling operation, in which a wobble is superimposed at swung sites, is able to suppress the field

Fig. 12 Comparison of aliasing rates for the triangular wave wobbling and the rectangular wave wobbling.
flicker that appears in the fine pattern or at abrupt edges of objects. We derived that the triangular wave swing or the triangular wave wobbling operation realizes high resolution image with lower aliasing. Also, we showed the aliasing evaluation method using the aliasing rate give a quantitative understanding of resolution including aliasing, and derived the optimum condition of the pixel aperture ratio $\alpha$ and the wobbling ratio $\beta$ for high resolution triangular wave wobbling operation.

In addition to the application for solid-state image sensors, it is easily understood that the swing and wobbling operations are useful for a high resolution method for display devices because a resolution of display devices can be denoted by the basic equations (1) and (4) for image sensors. This opens up a path to high resolution display devices particularly for projection applications by using high response display devices, such as digital mirror device (DMD) and antiferroelectric (AF) LCD, etc., in which signal for all pixels is able to be written during a vertical blanking period.

The resolution enhancement technique using the swing with the wobbling operation will become increasingly important for imaging systems that require high quality pictures as well as for display systems.

References


Nozomu Harada

He received the B.S and M.S degrees in electrical engineering from Shizuoka University, Japan, in 1968 and 1970, respectively. In 1970, he joined the R & D Center, Toshiba Corporation, where he engaged in research and development of high-sensitivity image tubes and CCD image sensors. In 1984, he joined the Toshiba ULSI Research Center, where he worked on the development of solid-state image sensors and managed developments of DRAM, Flash EEPROM and GaAs ICs.

Since 1993, he has been engaging in the developments of poly-Si TFT-LCD and other advanced LCD technologies in the Toshiba Display Device engineering Laboratory and the LCD R & D Center, respectively.

He received Suzuki Award and Niwa-Takayanagi Award from the Institute of Television Engineers of Japan in 1973 and 1984, respectively. He received two Invention and Innovation Awards from the Japan Institute of Invention and Innovation in 1990 and 1991, respectively. He also received Best Paper Award from Institute of Electronics Japan in 1998.

Mr. Harada is a member of the Institute of Image Information and Television Engineers, and the Japan Society of Applied Physics.

Okio Yoshida

He received the B.E., M.E., and Doctor degrees in electronics engineering from Tohoku University, Sendai, Japan in 1962, 1964, and 1973, respectively. Since 1964 he joined the R & D Center, Toshiba Corporation, Kawasaki, Japan and engaged in research and development of photonic imaging devices first vidicon-type camera tubes and later CCD imaging devices at the ULSI Research Laboratories. Toshiba Corporation. He then moved to the Technology Planning Coordination Division of the Principal Office and was dispatched to the Toshiba London Office as Toshiba Technology Representative for Europe from 1980 to 1989. Returning to Japan, he joined again the Laboratories and the Division. He retired from Toshiba Corporation in 2000 after having worked at the Corporate Planning Division and the International Relation Division. He is to take a professorship at Josai International University from 2001. He is a Fellow of IEEE, a Fellow of IEIE and a Chartered Engineer, a member of IEICE of Japan, IEICE of Japan and JSAP.