Color Calibration of LCDs

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Abstract

In this paper, we will discuss a particular color management of LCDs that consists of considerations of LCD's components. To remove an inter-channel cross talk of LCDs, we introduced a sensitivity function defined by the derivative of the S-curve of the LC material. In addition, we demonstrated an automatic calibration system for these color compensation parameters. Good performance of the color management of LCDs was achieved.

1. Introduction

For the purpose of implementing the color management of display, various reports of CRTs have been offering studies from many aspects including the examination of basic technologies,[1] performance assessment,[2] and model-ing.[3] The results of such studies are generally and widely utilized today as the color management specifications of display stipulated by the ICC[4] (International Color Consortium).

On the other hand, in the LCDs, which have been widely accepted as one of the popular displays, some of their unique color characteristics such as leakage light issues,[5] blue shift issue at lower gray,[6,7,8] and residual S-curve[9] have been pointed out. In spite of such different characteristics of LCD from CRT, the ICC color management for CRT has been employed directly for LCDs as they were CRTs.[5,9,10]

In addition to these approaches, there are some trials of more specific color management for LCDs.[11-13] It has been reported that better performance of the color management can be achieved when these methods are applied to the LCD.

In this paper, as a part of these researches, we will discuss a particular color management for the LCDs that consist of a consideration of LCD's components, and its calibration.

First, we re-considered fundamental characteristics of LCD from a viewpoint of characteristics of its components. There is a particular characteristic at LC-material called retardation that causes a change of spectral distribution of the transparency of LC-panel depending on the voltage applied. From a viewpoint of the retardation, we will discuss change of the color coordinates of primary colors of LCDs, which is dependent on the digital code value. Also we will discuss an example of inter-channel cross talk that will cause a lack of the additivity of the LCDs. Then, we will point out a fundamental property of the LCD that is clearly different from the CRT's.

Secondly, we will discuss a color management algorithm that is introduced to solve these fundamental color issues of the LCDs. The feature of the algorithm is how to decrease an effect of the inter-channel cross talk. We introduced a sensitivity function defined by the derivative of the S-curve of the LC material. By means of the algorithm, we will conclude some harmful color effects particularly in LCDs can be well removed and color management of the LCD is very well achieved.

2. Reconsideration of LCD Characteristics From a Viewpoint of LCD Components

In order to understand color issues of the LCDs essentially, it is necessary to study basic structure of the LCD in advance of the colorimetric evaluation. In this section, according to the characteristics of the components of the LCD, we explored basic properties of the LCD and pointed out which characteristics of the LCD should be considered as particular color management model for the LCD.

2.1 Analysis of Color Characteristics of the LCD From a Viewpoint of Its Components

From the view point of the color management, the LCD is roughly classified three parts: (1)glass plate containing some electrodes, thin film transistors and liquid crystal, (2) some optical components such as polarizer, color filter and back lighting system, (3) source and gate driver IC.

The relation between characteristics of these components and colorimetric measurement of the LCD is shown in Table 1. All these components influence color management.

Table 1. The Relation Between Characteristics of These Components and Colorimetric Measurement

Components		Related characteristics
Glass plate	Electrodes, TFT	Cross talk
	Liquid crystal	Displacement of the reference white and primary colors
Optics	Polarizer	Contrast ratio
	CF, and BL	Cross talk
Circuit	Source driver IC	Electro-optical response

2.2 Inter-Channel Cross Talk

Cross talk can be divided into two types: (1)Optical cross talk due to an insufficient response of the color filter, (2)Cross talk due to the capacitive coupling between electrodes. If such cross talk might exist, lack of the additivity law occurs because neighboring electrodes control different colors. For example, cross talk at blue channel ΔBlue can be expressed as

$$\Delta Blue = \phi(Red, Green, Blue) + \psi(Red, Green, Blue) \qquad (1)$$

where ϕ is an optical cross talk and ψ is a cross talk due to the capacitive coupling.

Figure 1 shows an example of the ΔBlue. The figure shows a spectral distribution of the blue channel, where the code value of the blue channel is fixed at 255 and code value of the green channel is changed from 0 to 255. About 7% of the cross talk has appeared. In this example, brightness of the Blue primary for full-saturated Cyan is about 7% brighter than for Blue. Thus, high performance of the color management for entire color range cannot be expected.

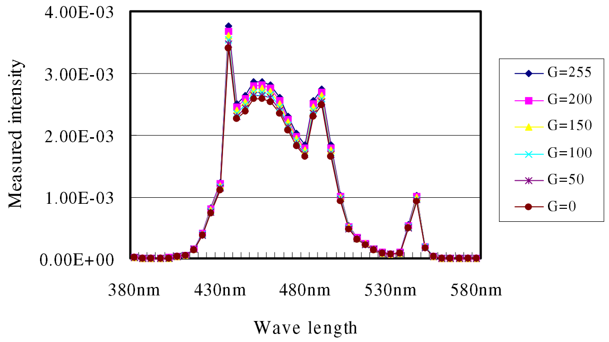

Figure 1. An example of the cross talk from Green channel to Blue channel.

2.2.1 Optical Cross Talk

Figure 2 shows an example of normalized spectral distribution of radiated color. There is an over lapping of each wavelength corresponding to the different primaries. Thus, for example, the Blue channel is not independent from the Green channel.

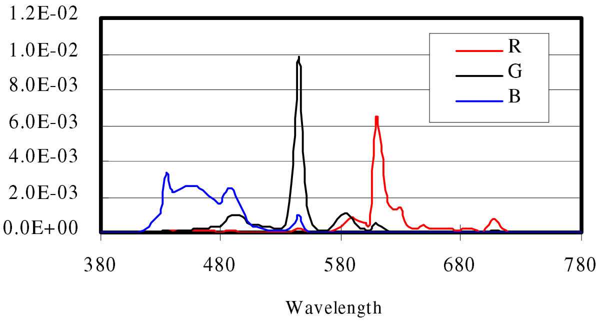

Figure 2. An example of spectral distribution of radiated color.

The amount of the cross talk that should be in proportion to the brightness of the related channel can be expressed as

$$\Delta_{\phi} Blue = kr*Red + kg*Green \qquad (2)$$

This cross talk can be removed by 3x3 linear matrix applied for signals proportional to optical intensity.

2.2.2 Cross Talk Due to the Capacitive Coupling

There is a parasitic capacitor between a source line and a sub-pixel electrode next to the source line. Therefore, the transparency of the sub-pixel must be changed according to the change of the voltage applied to next sub-pixel. This type of the cross talk only appears upon adjacent two sub-pixels.

Figure 3 shows a measured data of the cross talk. For the measurement, in order to reduce the optical cross talk, we used a blue LED array as back lighting system. Because there are no green components at the back-light, capacitive cross talk from Green to Blue can be isolated and measured. The data shown at the figure is change of Z of tri-stimulus values according to green change. The LCD measured was a new MVA (Multiple Vertical-domain Alignment)-LCD with normally black mode molecular structure.

The coupling from Green to Blue got larger when blue was at gray. Also the coupling was in proportion to the code value of the Green.

Figure 4 shows an example of absolute value of an additivity (R,G,B summing to White) error of the LCD measured at Fig. 3. The effect of the dark light level was removed. The graph shape of the Fig. 3 and Fig. 4 are almost the same. Around 180, the maximum error due to the coupling is observed.

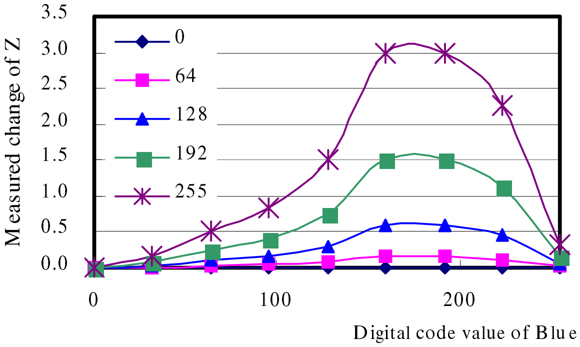

Figure 3. Measured change of Z according to the change of green. Z at full-saturated blue was 134.

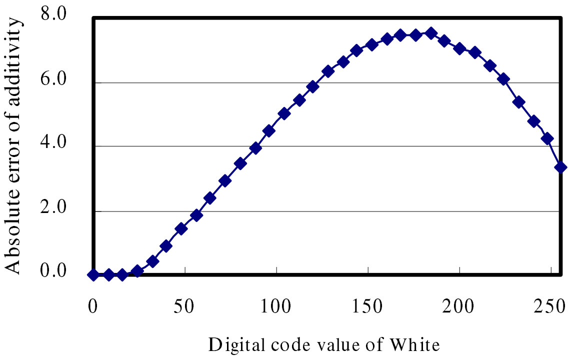

*Figure 4. Measured absolute error value of additivity. The error function was defined by Y(W) – [{Y(R)+Y(G)+Y(B)} – 2*Y(Bk)]*

2.2.3 Possibility of the Compensation of the Capacitive Coupling

Depending on the voltage applied, transparency of the LC-panel is changed along with the S-curve characteristics. Then, sensitivity of the transparency change against to the voltage change is in proportion to the derivative of the S-curve. Even for a small coupling, it is expected that considerable change in transparency should occur when the pixel is amplified at the sensitive voltage.

Figure 5 shows a S-curve function of the LCD measured at Fig. 3 and its derivative. The code value of the Blue for the maximum coupling from Green at Fig. 3, which is about 180, corresponds to the sensitive voltage.

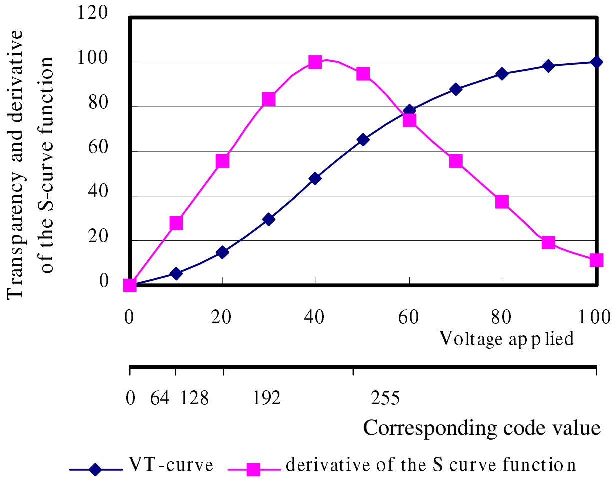

Figure 5. S-curve of the LCD and its derivative.

From the discussion above, we modeled this cross talk as

$$\Delta\psi B = S'(B)\{kr*R + kg*G\} \tag{3}$$

where S' is a sensitivity function corresponds to the derivative of the S-curve function that is a model of sensitivity of the transmissivity. Also R, G, and B are expressed as the voltage applied for each sub-pixel, and kr and kg is the coupling coefficient.

It is expected that effective removal of the cross talk and good additivity for entire color range can be achieved when an inverse compensation of the equation is applied.

2.3 Displacement of the Reference White and Primary Colors

2.3.1 Characteristics of Related Components

The transparency of the LC and the rotation characteristics of the light axis have variable wavelength characteristics, and such transparency and wavelength characteristics vary depending on the voltage applied.

This phenomenon, called retardation, is shown in Fig. 6. Measured transparency at code value of 255 was normalized into 1, and changing the code value, relative transparency for every wavelength was plotted.

In this example, normalized relative transparency of blue to red tends to increase at lower code value. In addition, especially around the wavelength from 450 to 500 [nm] where is correspond to blue, shape of the spectral distribution is changed according to the change of code value.

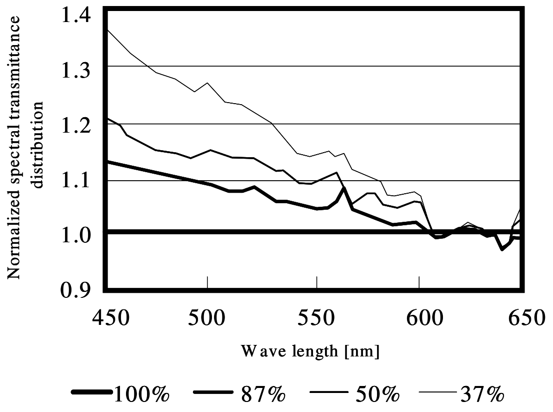

Figure 6. Normalized spectral transparency distribution of the LC panel corresponds to each code value. Measured MVA LCD in normally white mode.

Since LCD consists of a combination of the glass plate that have a characteristics mentioned above and a back lighting system, it is expected easily that the reference white at gray tends to shift toward blue because the color coordinates of the Blue primary change according to the code value.

Figure 7 shows an example of normalized spectral response of the Blue primary. Change in the spectral distribution can be seen. Also Fig. 8 shows a simulated variation of the color coordinates of the blue primary corresponding to Fig. 7, which is often observed.

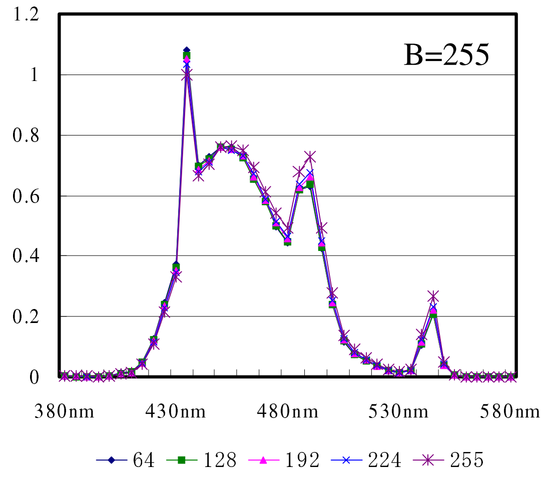

Figure 7. Normalized spectral radiance distribution of the blue channel

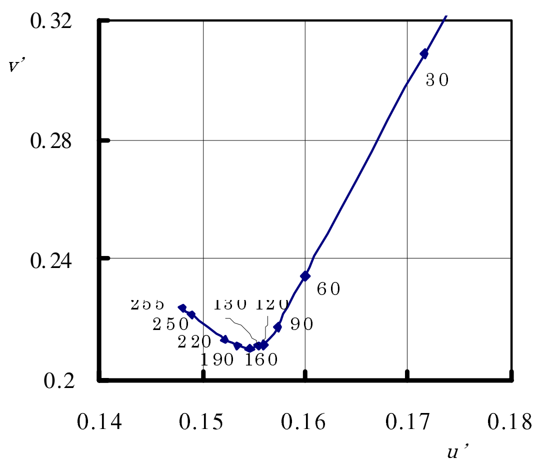

Figure 8. An example of the variation of the color coordinates of the blue primary. Numbers correspond to the code value.

2.3.2 Possibility for Compensation

Above-mentioned phenomena that are issues concerning the displacement of the color coordinates of the primary and reference white cannot be solved by a colorimetrical approach. Because the phenomena is based on the characteristics of retardation, in other words, based on the characteristics of the raw LC material, this issue must be considered for all kinds of LC-applied displays, though there might be differences in magnitude. Essentially, the LCD is a display that can hardly be applied the proportionality law.

To reduce these problems, the combination of the following is expected to be effective: (1)adjust the γ table to make the displacement of reference white minimize,[10] (2)define 3x3 matrix for the conversion of primaries by means of the least mean square error method.[12]

2.4 Contrast Ratio

The cut-off characteristics of the polarizer against the crossed nicol light slightly varies in terms of the wavelength. Thus, even if a good characteristic would be achieved at one specific wavelength, the contrast ratio may be subjected to certain restrictions for another wavelength. This is one reason for blue shift as well.

However, this leakage is a kind of static leakage, and therefore, it can be compensated easily by pre-subtracting corresponding values.[5,13]

Since most of recent LCDs keep their contrast ratio larger than 500:1, and the contrast ratio of the LCD under average room condition becomes better than the CRT's,[11,13,14] it is not required to be severe for the leakage.

2.5 Electro-Optical Response

Electro-optical response of the LCD is basically depending on the design of the source driver IC. As is well known, electro-optical response of the LC material has a S-shape characteristic. This S-shape characteristic has been converted into the typical γ characteristics as compatible for the CRT by means of source driver IC attached upon the glass plate directly.

It is expected that somewhat S-shape characteristics at electro-optical response of the LCD might still remain[8] if there were not a proper designing for the driver IC. In general, the latest driver ICs use non-linear voltage taps to achieve a good γ correction at middle gray. However, at white and/or dark end, it is hard to achieve a good response, and therefore, a γ look-up-table at the computer (or in the displays control system) would be required for the precise calibration.

2.6 Summary of the Color Issues of the LCD

The following four points cause problems of the color management colorimetrically, and relate to the essential problem inherent in current LCD devices, depending on the design matter of the components:

(1) The lack of the additivity due to the inter-channel cross talk.
(2) The non-proportionality due to the retardation.
(3) The leakage light due to the insufficient contrast ratio.[5]
(4) The residual of S-shape on electro-optical response of the LCD.[9]

These problems are essential issues to be considered for the color management of the LCDs since all they are concerning to the characteristics of the component of the LCD, and therefore, they must be common problems for all LCDs though there might be a difference of grade for different types. Therefore these problems should be solved explicitly in the framework of the color management of the LCD.

Since cross talk issue is one of the natures of the LCDs has not been discussed adequately, further discussion based on the essential characteristics of the LCDs is required.

3. Experiment of Color Management for LCDs

In order to consider an essential color management of the LCD, we made an experimental system. The system contains (1) Signal source, (2) Color management unit, and (3) LCD.

3.1 System Configuration and Experiment

The output of the signal source is XYZ signal with 16bits/channel, which was created under $\gamma=1$ condition. The LCD has 12 bits/channel performance, and no γ correction so that the S-curve of the raw LCD can be directly evaluated.

The color management unit contains three parts, that is matrix operation, γ correction, and cross talk removal.

(1) Matrix operation: In order to transform XYZ signal to RGB signal, 3x3 matrix that was determined by the least mean square error method[12] is used. Then, the optical cross talk described at 2.2.1 has removed.
(2) γ correction: RGB signal under $\gamma=1$ is transformed to S-curve of the LCD. γ table used is three independent 1-D tables. The tables were determined by the consideration of the retardation and the limitation of the contrast,[10] so

that the color coordinates of reference white and the primary stays as constant as possible.

(3) Cross talk removal: Cross talk due to the capacitive coupling is removed based on the idea described at 2.2.3. Note that an effect of the cross talk from B to R and from R to B have to be considered as an effect of next pixel, since the cross talk should be at adjacent two sub-pixels.

All the parameters were calibrated in order of (3), (2), and (1). For the calibration of the (1), 256 of reference colors were used. For the (2) and (3), both Fig. 3 and Fig. 5 were used.

3.2 Evaluation of Calibration Results

Displayed color error was evaluated using ΔE*94, where 4096 of color patches were created by the 16 levels of quantization of each X, Y and Z signal.

Table 2 shows a result. For the 4096 colors, both average color difference and its standard deviation are very low and maximum error is about 2.9. Also the additivity error was less than 0.5% for entire range of 0-255.

In order to clarify how cross talk removal at (3) is effective, we skipped the process of (3) and evaluated displayed color difference of similar 4096 colors again.

Table 3 shows the result. The average color difference is almost the same as table 2. However, maximum and standard deviation of the difference got larger than the table 2's. This means that there is a considerable deviation of color difference according to the color to be displayed.

Table 2. Performance of the Color Management Proposed Evaluated by ΔE*94 .

Average color difference	2.2
Standard deviation	1.2
Maximum	2.9

As mentioned above, cross talk removal (3) is very effective for reducing the color difference. However, since the sensitivity function is generated by the S-curve function, signal-processing depending on driver hardware is needed.

Table 3. Performance of the Color Management without Cross Talk Removal Evaluated by ΔE*94.

Average color difference	2.5
Standard deviation	6.9
Maximum	8.8

4. Color Calibration of the LCD

Suppose S-curve has been known, compensation for RGB signal of γ=2.2 is possible. For example, compensation value of the Blue channel can be expressed as

$$\Delta Blue = GS^{-1}[\ S'(GS(Blue))\ \{kr*GS(Red) + kg*GS(Green)\}\ ]\ (4),$$

where S' is the derivative and S^{-1} is the inverse of the S-curve function shown in Fig. 5. Red, Blue, and Green are input code value, and GS is a transform function from γ=2.2 to S-shape characteristic. GS must be taken into account of the correction shown in (2).

Since system γ has been known as 2.2, only if the S-curve could be determined in advance, most of the portion of the eq.(4) can be formed. Fig. 9 shows a system diagram of a color management framework of LCDs applied by the eq.(4).

In order to calibrate the parameters at the framework of the color management of LCDs shown in Fig. 9, we developed an automatic self-calibration system by means of a color sensor. Figure 10 shows a concept of the system.

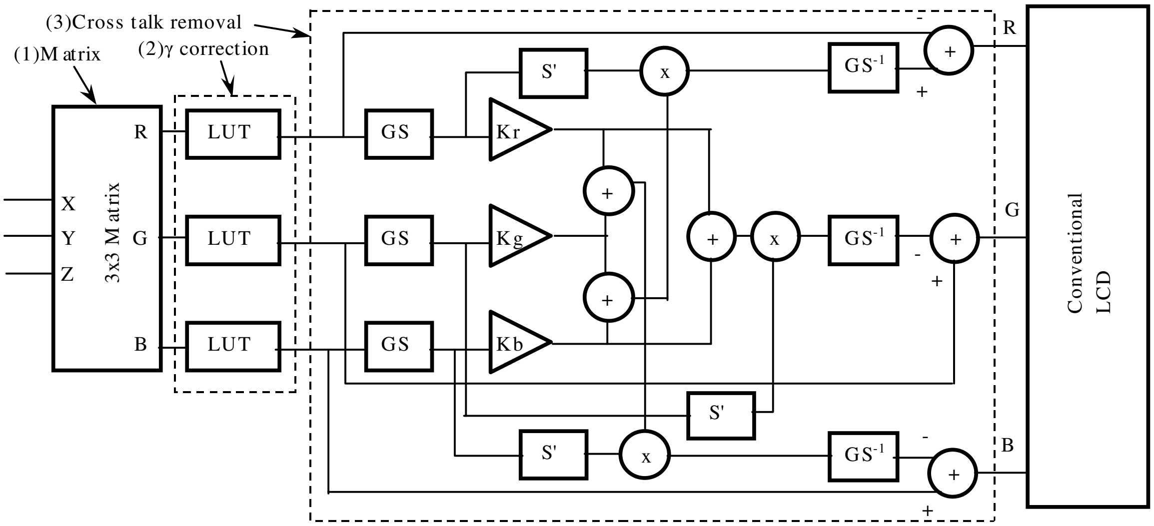

Figure 9. Color management method of LCDs.

By means of a CPU contained at the LCD monitor, reference colors are generated and displayed. The sensor measures their color and feed the measured data back to the CPU. Then, the CPU put appropriate values of parameters for the LUTs and coefficients.

We evaluated a prototype of this system as sRGB monitor. Fig. 11 shows an example of its evaluation result. For all of the reference colors and reference white, excellent performance can be seen as expected at Table 2. Application for high-end monitor can be expected.

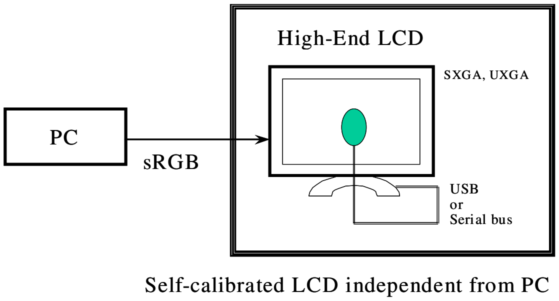

Figure 10. Conceptual diagram of a calibration system.

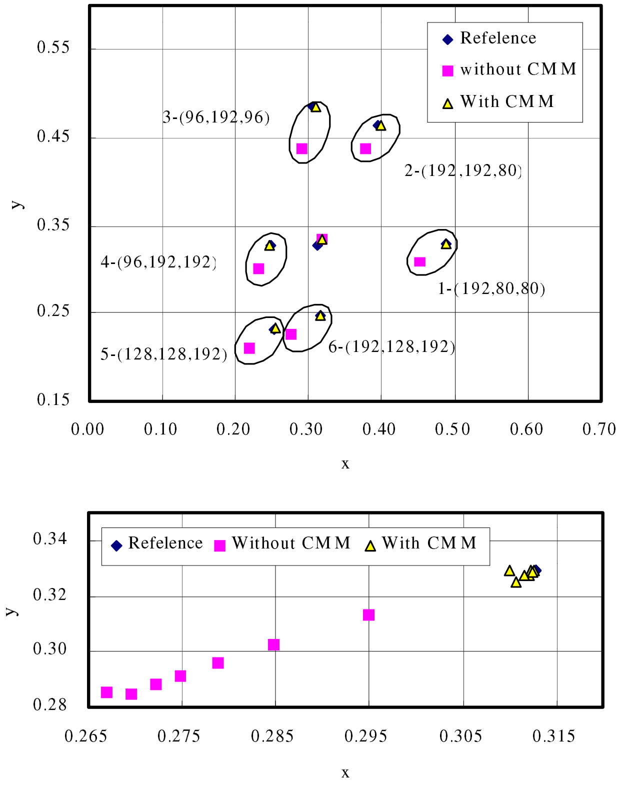

Figure 11. Upper: Performance evaluated with WHQL standard color patches. Bottom: Performance with IEC61966-4 patches.

5. Conclusion

In this paper, we discussed a particular color management for the LCDs that consist of a consideration of LCD's components.

Exploring the characteristics of the components of the LCD, we described that the LCD is a display that has different color characteristics from CRT's, essential-ly. We demonstrated that removing the crosstalk problems is effective to make LCD's color performance better. In order to avoid the cross talk, we propose a method based on the S-curve characteristics. In addition, we demon-strated an example of an automatic self-calibration system for these color compensation parameters.

For the precise color management of the LCD, since the S-curve is one of the most important characteristics for the cross talk as well as a reproduction of the electro-optical response and is a particular characteristic for LCDs, the S-curve should be handled as one of the special parameters of the color performance of the LCDs.

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Biography

Yasuhiro Yoshida is a manager of the LSI Group, Sharp Corp. His main activity is developing LSIs for improving the picture quality of LCDs. He received his Ph.D. degree in 2002 in color management and its circuit design for LCD.