Optics of Color Filter

Sumitomo Chemical Co., Ltd.
IT-Related Chemicals Research Laboratory
Kiyoharu NAKATSUKA

Theoretical limits of characteristics of color-filters for LCDs are investigated. The results and design tools for (1) chromaticity of 3-primeries, (2) lightness, pigment particle size, (4) light loss by ITO, (5) special color filter for LED back light, and (6) microscopic spectrophotometry are presented.

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Introduction

Developments in the field of information technology are eye opening, and Sumitomo Chemical lays stress on allotting management resources to this field. The situation in research is such that new proposals are made daily in response to the rapidly changing demands of customers. Doing this requires accumulation of wide range of fundamental technology and the high level of adaptability, but there are limits to this. It is thought that establishing the forecasts of technical development and pointing out the limit of that technology are helpful in this situation. In semiconductor lithography, it has become clear that there are limitations of the design rule by the wavelengths of light used. Therefore, there has been a shift from g- and i-lines to shorter wavelength excimer lasers, such as KrF, ArF and F_2.

There is nothing so broadly and clearly recognized in the field of display materials. However, a similar prospection can be established and certain technological limitations can be known. We think it is possible to save time thinking and experimenting and make the research and development process more efficient based on this prospection.

In this article, limiting this to LCD color filters, we will investigate the following issues by the optical considerations and basic data:

1. What are the three primary colors?
2. Maximum attainable Y value of color filter
3. How fine should pigment be?
4. Eliminating light loss of transparent conductive layer
5. Wide gamut LCD and its color filter
6. Measuring color of fine pixels in color filter

Light cannot be viewed. The light of a searchlight can be seen to a certain extent as it passed through smoke, but you cannot observe the light that goes into the eyes of the person sitting next to you and watching TV. You cannot even observe it in smoke or fog. Therefore, it is difficult to understand what we say about light intuitively. For easier understanding, figures rather than tables and equations are employed. Please see the references for the details of the technology.

1. What are the three primary colors?

As a preparation for the following explanations, let us discuss the three primary colors. Unless specifically mentioned, the source for this section is "*Color Science*" by G. Wyszecki and W. S. Stiles[1].

<<Trichromatic Principle: The three primary colors are red, green and blue>>

According to the Young-Helmholtz three-component theory,

(1) The visual system is made up of three types of photoreceptors or nervous fibers.

(2) These photoreceptors have mutually overlapping spectral sensitivities with peaks in the red to orange, green and blue to purple ranges.

(3) The sensation of color is determined by the sum of the signals from these three types of receptors, and physiologically, the three primary colors turn out to be red, green and blue.

<<Vector representation of color/ Infinite number of sets of three primary colors>>

Grassman, who was a pioneer in vector analysis, formulated the trichromatic theory using vectors (Grassman's law). Letting the three primary colors with certain intensity as a unit vector, all colors can be represented as single points in a three-dimensional space (position vector). Here, A = B means two color stimuli (colored light) A and B are seen as the same color (color match). A + B means mixing B into colored light A (additive color mixing), and αA represents the intensity of colored light A is increased or decreased by α times. A – B = C means that A = C + B. Therefore, coordinate transformations are possible, and in the end, regardless of the physiological significance, any set of three-color stimuli that are linearly independent (none of the stimuli can be color matched by mixture of the other two) can be made up of the three primary colors.

<<1931 CIE Colorimetric System>>

According to Grassman's law, the Commission International de l'Eclairage (CIE, 1931) recommended its colorimetric system. In this system, a color is represented as a point (X, Y, Z) in an XYZ space, and X, Y, Z are called tristimulus values. The spectral sensitivities of the three types of photoreceptors of the CIE colorimetric system are shown in **Fig. 1**. However, these spectral sensitivities are not physiological, and they are called the color-matching functions. Furthermore, the three primary colors were selected colored lights that do not actually exist, and luminance can only be expressed by tristimulus value Y. In other words, luminances of color stimuli corresponding to the primary colors X and Z are zero. Therefore, letting x = X/(X + Y + Z) and y = Y/(X + Y + Z), colors can be represented in a two-dimensional plane, and luminance is represented separately by the Y value. (x, y) is called the chromaticity coordinate and this diagram a chromaticity diagram. The chromaticity coordinates may simply be called chromaticity. **Fig. 2** shows the CIE 1931 chromaticity diagram. The horseshoe-shaped line traces monochromatic light (spectrum locus), and their wavelengths are depicted in nm units. The straight line joining the two ends of the spectrum locus (purple line) is the plot of the additive mixtures of these monochromatic lights in various proportions. All real colors can be plotted within the range bounded by the spectrum locus and the purple line. The tristimulus values and chromaticity coordinates of a color stimulus can be calculated with the measured spectral distribution of the color stimulus and the CIE color-matching functions, and any color stimulus can be represented. The Grassman's vector notation has been refined and a paper that explains the elegant method for deriving the CIE 1931 color-matching function has been published, in 1997 2).

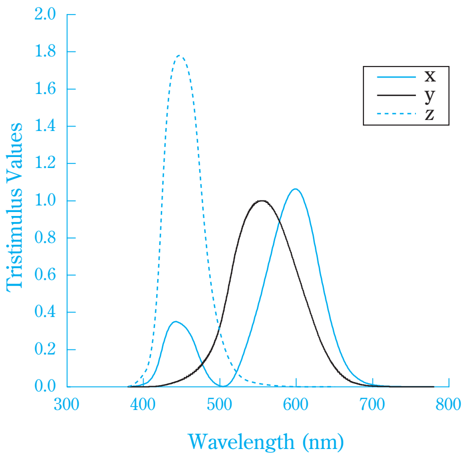

Fig. 1 CIE 1931 color matching functions

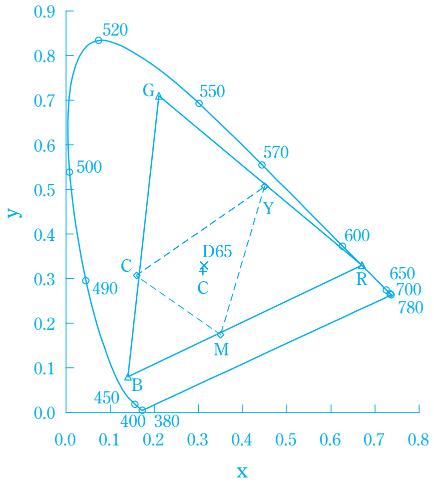

Fig. 2 CIE 1931 chromaticity diagram

<<Color of object and light source>>

The colors of non-luminous objects (object colors) can be calculated from the spectral distributions of light transmitted or reflected from these objects. The tristimulus values of object colors are normalized by the Y value of the perfect reflecting diffuser or perfect transmitting diffuser (a spectral reflectance or transmittance are 1.0 (100%) in all visible wavelengths). The spectral distribution of the light emerged from an object is the product of spectral transmittance or spectral reflectance of the object and the spectral distribution of the light illuminating it, therefore the illuminating light source must be specified for measuring object colors. The CIE has recommended the set of such spectral distributions called the CIE standard illuminants. Fig. 2 shows the chromaticity coordinates of the standard illuminant D_{65} and the illuminant C. D_{65} was determined based on averages of actually measured of natural light. The illuminant C was defined to achieve the light source with the color filter on the tungsten filament lamp for the same purpose, so the method for preparing the standard light source C was also specified. At present, the illuminant C has been removed from the CIE standards, but it is still widely used in the field of display materials. It is clear that the light sources illuminating LCD's are the backlights in the LCD modules, but the illuminant C is commonly used for specifying color filters.

<<Four primary colors: extending color gamut>>

According to Grassman's law, the representative point of any additive mixture of real color stimuli lies between the chromaticity points of the constituents on the straight line connecting them. In other words, chromaticity points of all colors have to form a convex set in the chromaticity diagram. With three colors, any additive mixture lies on the triangle with the three corresponding points of the constituents as vertices. If negative color mixing is allowed, colors lie on the extension of the line connecting these two constituents can be additively created. With three colors, all colors can be created with any set of three linearly independent primary colors. However, display devices such as CRTs, PDPs, ELs and LCDs cannot achieve negative color mixing. Therefore, the range of color that can be displayed by the display device (color gamut) is limited by the selection of three primary colors of the device. The larger the area of the triangle created by the three primary colors on the chromaticity diagram is, the more wide the range of colors that can be displayed by this device. This area is also called the color reproduction range or color reproduction area. To move the origin for the chromaticity coordinates on one of the primary colors, and one-half of the absolute value of the outer product of the new position vectors for the remaining two points is the area of the color gamut.

As can be seen from Fig. 2, it is not possible to display all colors with display devices, no matter how the three primary colors are selected. Since the more wide color gamut is achieved, red, green and blue are most frequently used as three primary colors. To increase the color gamut, it is considered to add one more primary color, and making the gamut into a rectangle. This gives the four primary colors, and the color gamut is gradually increased by increasing them to five and six primary colors, and so on, but a spectroscopic imaging device becomes necessary. Relating to imaging, recording and transmission systems, the four primary system is not practical. Imaging devices only convert light into an electric signal and negative color mixing is allowed, so it is possible to select any set of three primary colors if they are linearly independent. Actually, C, M, and Y primaries shown in Fig.2 are adopted in most video cameras. As can be seen in Fig. 2, C = G + B, M = B + R and Y = R + G are satisfied, so the light loss due to the color filter is reduced and higher sensitivity is achieved. However, there are problems with noise and the metamerism mentioned below, therefore the selection of the three primary colors is also important in imaging devices, and research is still continuing.

<<Saturation of color>>

As is clear from the preceding explanation, achromatic colors, such as white, gray and black, lie on the central area of the horseshoe boundaries in the chromaticity diagram and the colors nearer to the periphery are more saturated. Therefore, the distance to the white point (usually D_{65}) is an approximate measure of saturation of the color. In other words, the mixing ratio of the white light to the monochromic light can be an index of saturation. More exactly, the excitation purity is defined, but the details are not mentioned here.

<<Metamerism>>

As can easily be conceived from the trichromatic principle, it is possible that two color stimuli with different spectral distributions color match. This phenomenon is called metamerism, and the pair of color stimuli is called metameric pair. With object colors, two objects having different spectral transmittance or reflectance color match under an illumination, but this match will break under other illuminations. There are infinite numbers of metameric pair for any given color. Care is necessary when developing a color filter referring to a color sample. Metamerism is often left out of consideration.

<<Reconsideration of the trichromatic principle>>

According to Grassman's law, real colors form a convex set in the chromaticity diagram, and the data for the 1931 CIE colorimetric system follows suit. However, it may not form a convex set, and the Grassman's law is broken.3) In case of strong metamerism (the difference in spectral distribution of color stimuli is large), particular care is necessary.4) J. Zolid5) has said that if the differences between observers were corrected for, this problem was greatly improved. However, there has been criticism for a long time that the cause is the assumption that "the sensation of color is determined by a linear combination of the signals from three types of receptors" in the trichromatic principle. Even at present, researches are continuing on the nonlinearity of the responses of the receptors, the brain and the transmission system between them.6)

The CIE color matching functions are considered as the spectral sensitivities of the three types of receptors, but this is not physiological. The existence of three types of receptors responsible to red, green and blue lights through microscopic spectrophotometry of the retina has been confirmed. These three types of receptors are named L, M and S (Long, Middle and Short wavelength sensitive), and researches into the spectral sensitivity and nonlinear characteristics are continuing7).

2. Maximum attainable Y value of color filter

Saturation and Y value of color filter are required to be as high as possible. These requirements are based on the needs for low power consumption and high quality of color reproduction. So, how high can Y value of a color filter be obtained? Is there a theoretical limitation? **Fig. 3** shows the spectral transmittance of a color filter for a typical LCD-TV. The color gamut of LCD with this color filter is 72% based on the standard (100%) of the color gamut of the NTSC (National Television System Committee) specification under the standard illuminant C. An attempt can be made to increase the Y value while maintaining this color gamut by expanding the peaks tops of the spectral transmittances of red, green and blue. **Fig. 4** shows the transmittance when each peak of the transmittances of the color filter shown in Fig. 3 is expanded to 1.0. Each transmittance curve is approximated by the Gaussian function for the probability distribution, and each chromaticity of the primary colors, red, green and blue, is adjusted to the same as that of the color filter in Fig. 3 within for decimal places. Therefore, the color gamut does not change. By this expansion of the peaks, the Y values for each of the colors, red, green and blue, are increased to 18.4→18.5, 55.3→70.3 and 9.0→12.6, respectively. Since the red peak was already higher before the expansion, the increase of Y is smaller compared with that of green and blue.

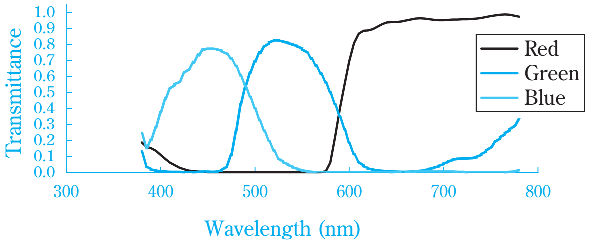

Fig. 3 Spectral transmittance of Color Filters for LCD-TV

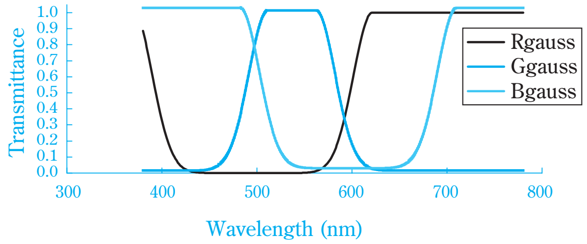

Fig. 4 Spectral transmittance of Ideal color filters having peak tops of 1.0.
The chromaticity coordinates are same as that of the color filters indicated in Fig. 3.

The transmitting band must be expanded to attempt further increase of the Y values, but if so, chromaticities will be change, and the saturations will decrease. Thus, the transmittance curves depicted in **Fig. 5** have two values either zero or unity and the transitions between them moved along visible spectrum to adjust the chromaticities. The objects with the transmittances depicted in this diagram have the theoretically highest Y values at the given chromaticities (see Reference 1) for details). This is called the optimal color. As with Fig. 4, these optimal colors are also adjusted in chromaticity within four decimal places. In Figs. 4 and 5 the transmittance curves of red, green and blue are shifted a little along the vertical axis to make them easier to distinguish.

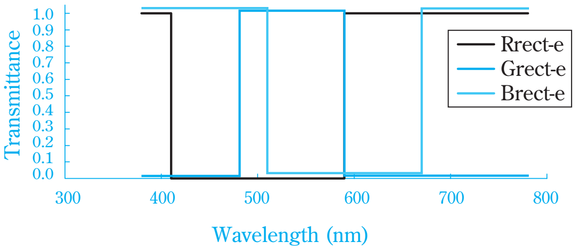

Fig. 5 Spectral transmittance of optimal colors. The chromaticity coordinates are same as that of the color filters indicated in Fig. 3.

Now, how about the brightness of the optimal colors? **Fig. 6** shows the color gamut vs. the Y value of displayed white (average of the Y values of red, green and blue). The data of color filter for notebook PC and the corresponding optimal colors are shown in Fig. 6. There are still large distances from the theoretical limits. Here, the data of notebook PC and TV are discontinuous, and they are not connected. This is because the hue of the three primary colors of the notebook PC and the TV are different. In the case of the notebook PC, the green tends to yellowish green, and the blue tends to greenish blue so as to increase Y values. If the red is moved toward orange, the Y value also increases, but this is not done in this color filter. **Fig. 7** shows the chromaticities for these color filters.

Fig. 7 shows the three primary colors of the European Broadcasting Union (EBU) standard. These three primary colors are substantially the same as those of high definition television and the sRGB (for computer monitor displays) standards, and they are representative of the primary colors in TVs at present. These standards were determined with CRTs in mind, and the Y value of the blue is 8.6, even for the optimal color. It is remarkably dark. Therefore, chromaticity of blue of actual color filters for TV is shifted a little in accordance with notebook PCs. To retain the color gamut the same, the chromaticity coordinates are shifted to higher saturation. Because of this, the red is darkened, but the Y value of resultant white is conserved.

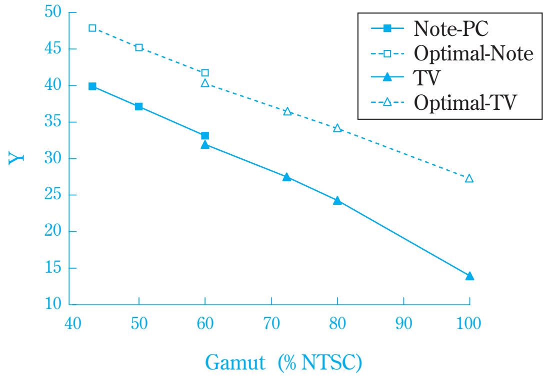

Fig. 6 Gamut vs. Y values of color filters for TV, note-PC and there optimal colors.

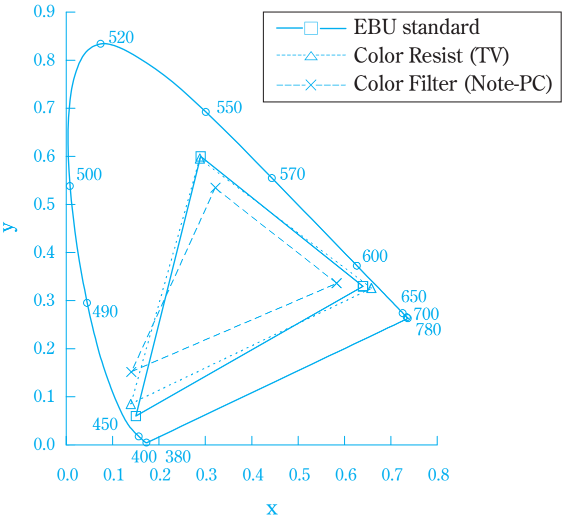

Fig. 7 Chromaticity coordinates of various primaries

3. How fine should pigment be?

There is still large gap between Y values of actual color filters and that of correspondent optimal colors. It is said that pigments with smaller particle size will lead the Y values of color filters to larger. If so, how fine should they be? **Fig. 8** shows the calculated spectral transmittances of a pigment (C. I. Pigment Violet 23) with various diameters of 1.0µm to 0.001µm. Grinding pigment particles causes the change of tinting strength and hue. The hue change cannot be corrected without adding other pigments, but saturation can be maintained constant by adjusting the concentration (amount added) of the pigment. Here, let the distance from the white point (standard illuminant C) on the chromaticity diagram be measure of sat-

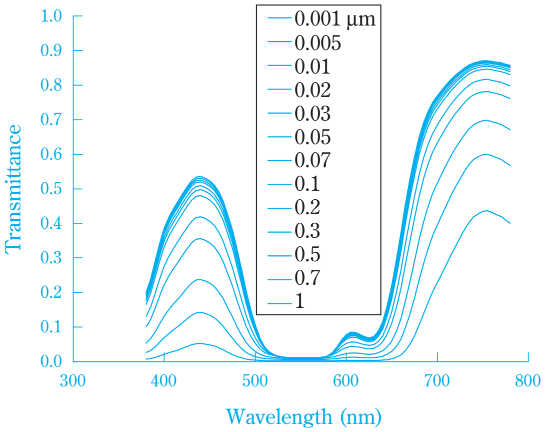

Fig. 8 Spectral transmittances of various particle sizes of C. I. Pigment Violet 23

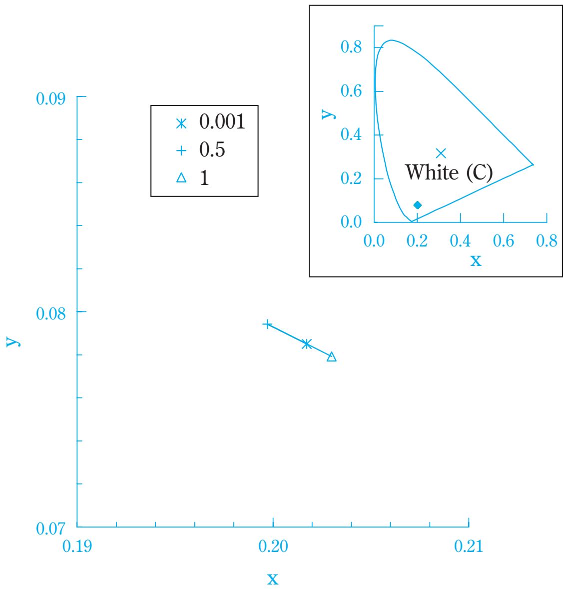

Fig. 9 Chromaticity diagram of various particle sizes of C. I. Pigment Violet 23

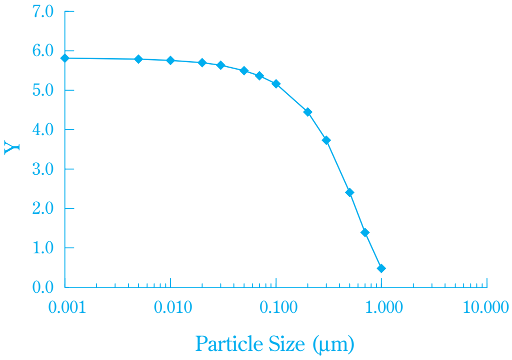

Fig. 10 Particle size vs. Y curve. C. I. Pigment Violet 23

uration. As can be seen in Fig. 8, when the pigment particle size is decreased, the peak to valley height of the transmittance curve increases and the curve resembles that of the optimal color more closely. However, this increase of the peak to valley height is saturated around 0.02µm. The changes of the Y value at this time are shown in **Fig. 10**. In this figure, it can also be seen that the increases in the Y value are limited at around 20nm. Therefore, in this case, 20nm is sufficient and further grinding is expected almost no effect.

The approximate limit of Y value by pigment grinding becomes obvious from above simulation, but the small amount of light scattering due to the pigment particles in LCD color filters is another issue. Since polarizers with polarization degree of approximately four-nine (99.99%) are built in LCDs, the quality of display can be deteriorated even by such a small amount of scattering. This light scattering can also be reduced by grinding the pigments to smaller particles. The degree of scattering in an LCD color filter is expressed as the ratio of two luminous transmittances (Y values) of the color filter sandwiched between parallel polarizers and between crossed polarizers. This ratio is called the contrast ratio. (Contrast Ratio) = (Y parallel)/(Y crossed). This contrast can be estimated by calculation, but here we will show experimental data. In this experiment, plurals of same kind of pigment differing only in particle diameter were first prepared, and next, color resists with these pigments completely dispersed into the primary particles were prepared. This kind of experiment is difficult, both in terms of equipment and technology for anyone other than a pigment maker like Sumitomo Chemical. The results of this experiment are shown in **Fig. 11**. The pigment is C. I. Pigment Red 177. In the figure, the particle diameter is expressed by specific surface area (surface area per g, m^2/g). The diameter of spherical particle is inversely proportional to the specific surface area, and with this pigment (specific gravity being involved), $60m^2/g$ corresponds to 0.067µm and $120m^2/g$ to 0.033µm. Even if the particle size is reduced to 0.033µm, the contrast does not saturate, and no limit is seen. **Fig. 12** shows the scattering coefficient (scattering efficiency) vs. particle size for C. I. Pigment Red 177 calculated by Mie scattering formula. Also in this figure, no limit of contrast is found. It is valid to continue the grinding pigment up to required level. In addition, as can be seen in Fig. 12, residual course particles diminishes the effect of grinding pigment to reduce average particle size because the scattering increases rapidly with increase of particle diameter.

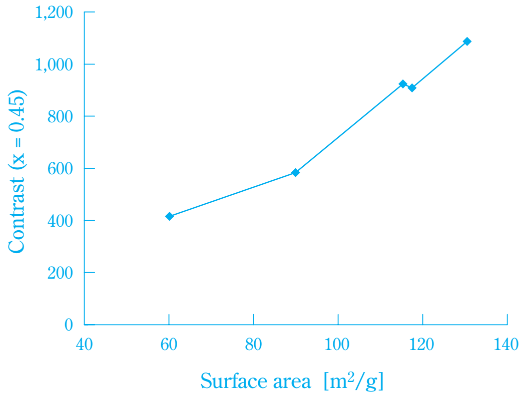

Fig. 11 Surface area vs. Contrast curve

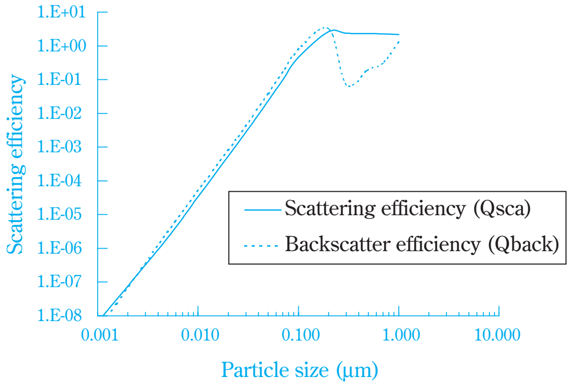

Fig. 12 Particle size vs. scattering efficiency of C. I. Pigment Red 177, the wavelength is 550 nm

In the above simulation, the scattering characteristics of a single particle are first calculated using Mie or Rayleigh light scattering model.[8] The efficient methods for calculating the Mie scattering formula have been developed,[9), 10] and the calculations can be done with a personal computer. However, these models are limited to spherical particles, so the use of T-matrix model[11] or coupled wave analysis[12], etc. is proposed. The spectral complex refractive index (real part being ordinary refractive index and imaginary part being absorbance) is required for these calculations, and it is necessary to produce a single crystal of pigment[13]. However, it is also reported that sufficient precision can be obtained by pressing to solidify the pigment powder[14]. Next, multiple scattering characteristics due to particles dispersed in colored layer is calculated from these scattering characteristics for a single particle, and the transmittance or reflectance of the colored layer is obtained. This calculation of multiple scattering requires the radiative transfer equations[15]. Practically, multiflux method[16)–18] that simplifies the calculations by dividing the space into few parts similar to the finite element method is used.

By the way, sunlight is scattered by the gaseous molecules in the atmosphere, and the light from blue sky is strongly polarized. **Fig. 13** shows the angular distribution of scattered light by the pigment shown in Fig. 12 using polar coordinates. 0.50, 0.10 and 0.01 are particle diameters in μm, and S is the s polarization component of the scattered light (vibrating perpendicular to the surface of the paper, "s" taken from the German word *senkrecht* /TE mode in the electromagnetic analysis); P is the p polarization component (parallel to the paper surface, taken from the English word *parallel*/TM mode in the electromagnetic analysis), and U is the unpolarized light, the average of the s and p components. For smaller particle, forward and back scattering appears equally. In addition, when the particle size decreases, significant polarization splitting of the scattered light appears. The polarization of skylight is due to this phenomenon.

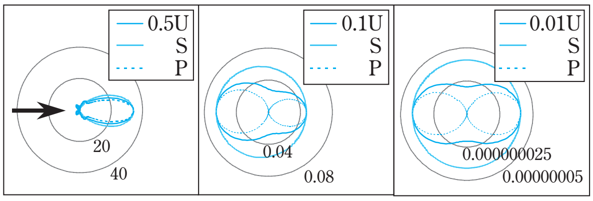

Fig. 13 Polar plot of scattered light by C. I. Pigment Red 177. The diameters are 0.50, 0.10, 0.01 μm. U:unpolarized, S:s-polarized, P : p-polarized

4. Eliminating light loss of transparent conductive layer

An overcoat, transparent conductive layer (usually ITO) and alignment layer are applied to the color filter. Since, among these, ITO has a high refractive index, a large loss of light due to reflection at the boundary occurs. If a color filter with ITO is measured, the loss is about 10%. However, if an alignment layer (PI) is applied to this, the loss decreases to 2–3%. Therefore, the alignment layer is considered as an antireflection film. Thus, the idea of changing the thickness of the alignment layer to reduce the light loss arises, but it does not work. Since the refractive index of the alignment layer and that of the liquid crystal are close, the light loss does not substantially change by adjusting the thickness of the alignment layer. Whether an alignment layer is applied or not, the light loss due to ITO is not change if the color filter built in a LCD cell. **Fig. 14** shows the calculated spectral transmittance of the color filter alone, with the ITO applied, with the ITO and the alignment layer applied, and with the liquid crystals directly in contact with the ITO. In this case, the reflections from glass substrate, etc., are ignored. The results of calculations in Fig.14 agree well with the experimental results mentioned above. In addition, it was confirmed that the alignment layer plays almost no antireflection role within the liquid crystal cells.

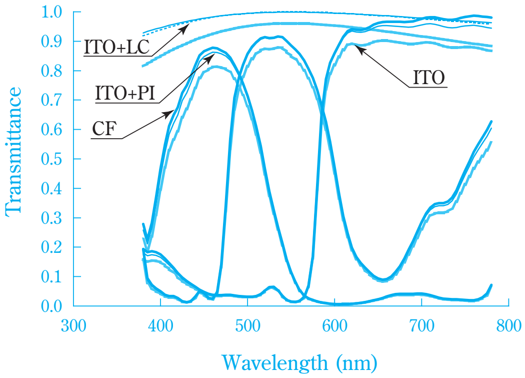

Fig. 14 Light losses of color filters caused by ITO. CF:color filters without ITO, ITO:with ITO, ITO+PI:with ITO and orientation layer, ITO+LC:with ITO without orientation layer and with liquid crystal

However, the effect of the ITO thickness is large. **Fig. 15** shows the relationship between transmittance and the thickness of ITO with alignment layer. The Y value vs. the thickness of ITO is shown in **Fig. 16**. In this instance, the optimum thickness is around 140nm. Since the complex refractive index changes according to the growing conditions of ITO, the actual measurements are necessary.

The calculations above are done as follows.[8] Characteristic matrix of each layers are set up with the measured complex refractive index and thickness of each layer and multiplied them in the order of lamination. Then the product is the characteristic matrix of whole the layer. The transmittance and the reflectance of whole the layer are calculated using the elements of the matrix obtained.

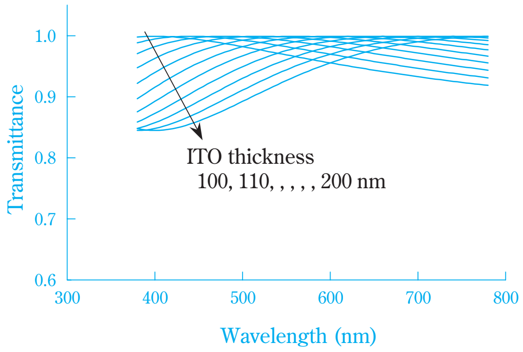

Fig. 15 Spectral transmittance of various thickness of ITO layers with PI

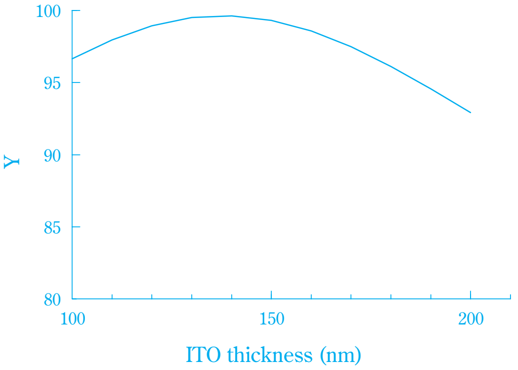

Fig. 16 Thickness vs. Y values of ITO layers with PI

5. Wide gamut LCD and its color filter

According to wide spreading of desktop publishing (DTP) and Internet shopping, the requirements for wide gamut LCDs that exceed the color gamut of the EBU and sRGB standards are growing[19]. Along with this, adopting LED back light is the most promising method to realize such a wide gamut LCD.

Fig. 17 shows the spectral distribution of various backlights. Standard illuminant C emits continuous spectrum, but the LED-1 in Fig. 17 emit only red, green and blue light efficiently. The three-band cold cathode fluorescent lamp that has conventionally been in wide use also emits sharp lines in the red, green and blue regions but it emits also many other wavelengths of light (3-band CFL in the figure). Moreover, the white LEDs shown as LED-W in the figure emit a continuous spectrum and are not suitable as the backlights for wide gamut LCDs. The spectral distributions of the three-band cold cathode fluorescent lamp and the LED are just an example, and there are many variations of characteristics. In addition, each intensity of red, green, and blue lights emitted by LED-1 is independently adjustable and it is easy to match wide range of correlated color temperature.

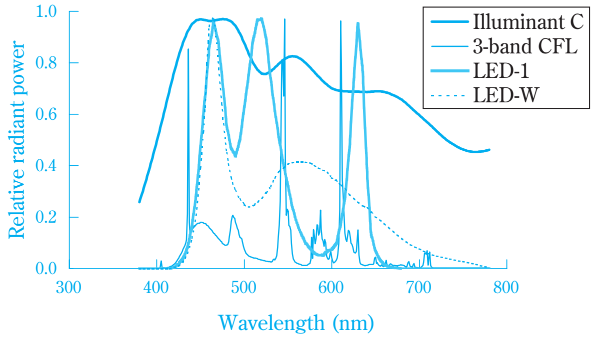

Fig. 17 Spectral power distribution of several back lights and illuminant C. 3-band CFL : 3-band type cold cathode fluorescent lamp, LED-1: Red, Green and Blue LED's, LED-W: white LED

Is any special color filter necessary for wide gamut LCDs with LED back lights? **Fig. 18** shows the relationship between the color gamut and the Y value (Ywhite) when the TV color filter shown in Fig. 6 is combined with the various back lights mentioned above. This color filter was designed for 72% of color gamut under the illuminant C and the Ywhite is 27.5. Changing the backlight to the three-band cold cathode fluorescent lamp, the color gamut increases to 75% and the Ywhite to 27.7. Furthermore, if the backlight replaced by LED-1, the color gamut becomes 94% and the Ywhite 30.1. Although the color filter remains no change, the large increases both in the color gamut and the Y value are obtained. By a slight adjustment of this color filter, the color gamut of 100% can easily be obtained, and the Ywhite is 28.1 at that time. **Fig. 19** shows the color reproduction ranges for the combination of this color filter and these backlights. There is little difference between the color filter designed for color gamut of 72% with standard illuminant C and the one with a color gamut of 100% for the LED-1, so we can see that just a small correction is sufficient. However, if we use the color filter with color gamut of 100% for the illuminant C as shown in Fig. 6, we can only get a Ywhite of approximately 14, it is extremely dark. In addition, the Ywhite of the optimal color corresponding to this color filter under the illuminant C is 27.3 (see Fig. 6), so it means that if LED-1 is used, a color filter having Ywhite greater than that of the optimal color for the illuminant C can be obtained. Therefore, it seems that we will have to say that "that the optimal color is not always optimal", but we must remember that the tristimulus values of object colors are normalized by the Y value of perfect diffuser. The combination of three LEDs efficiently emit red, green and blue light, but the continuous spectrum of illuminant C includes

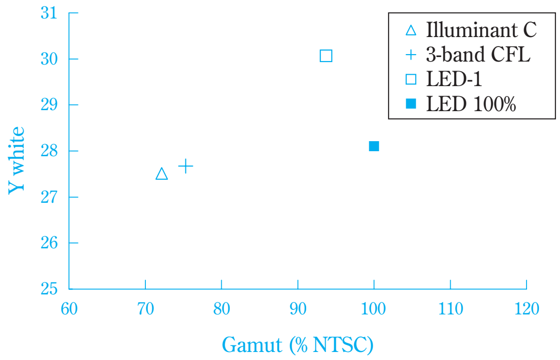

Fig. 18 Gamuts vs. Ywhite of the color filter shown in Fig. 6 with several back lights, 3-band CFL: 3-band type cold cathode fluorescent lamp, LED-1: combination of Red, Green and Blue LEDs, LED 100%: slightly modified color filter with LED-1

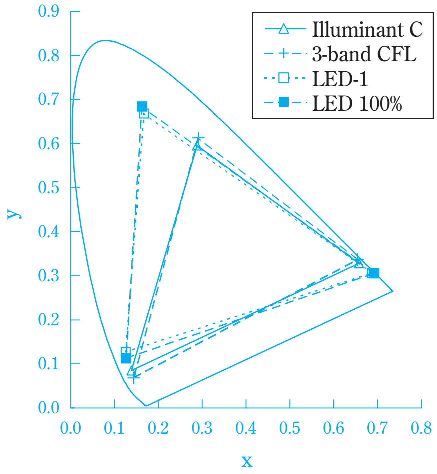

Fig. 19 Color gamuts of the color filter indicated in Fig. 6 with several back lights, 3-band CFL: 3-band type cold cathode fluorescent lamp, LED-1: combination of Red, Green and Blue LEDs, LED 100%: slightly modified color filter with LED-1

a great deal of light other than red, green and blue. Object color, including optimal color, is defined by its spectral transmittance or reflectance and illuminating light.

Above discussion is about changing the backlight for the color filter designed for color gamut of 72% under the illuminant C and modifying its color, but it is ignored whether the chromaticity coordinates of the three primary colors match to the NSTC standard, whether the chromaticity of the resulted white coincide to the standard value, etc. Moreover, the pigment concentration and the film thickness of the colored layers are not considered. For example, the color filter with 100% gamut under the illuminant C requires triple the film thickness or pigment concentration of that of the color filter with gamut of 72%, then producing this is substantially impossible. Besides the above, it is also necessary to specify the chromaticities of displayed black and gray to design practical color filters. It is extremely inefficient to carry out this kind of design work based on trial and error or with matrix data, and obtaining optimum solution cannot be expected. New efficient optimization method is necessary.

The above color design is not much different from that carried out by dye and pigment manufacturers on everyday basis. The optimization methods used for the production and application of colorants[20)] can also be used with some modifications. The major tools are the color assessment system and the computer color matching system. It is said that when reference 20) was published, solving nonlinear simultaneous equations is quiet difficult. But after the publication of Allen's method[21)], it becomes possible to use a variety of optimization calculation methods[22), 23)], so optimum solutions were easily obtained without falling into local optimum or slow convergence. In addition, it also makes possible to use linear programming methods[24)] that enables to obtain information for several solutions, such as the second and third optimums. In case of trade-offs problems between reliability and chromatic characteristics to that any strait-forward optimization method can apply, these second and third optimums are very powerful.

6. Measuring color of fine pixels in color filter

Each of pixels of three primary colors in color filter is a fine rectangle of approximately 50 × 200 – 80 × 300µm, and the color of these small pixels are measured with microscopic spectrophotometer which is combination of microscope and spectrophotometer. An area of approximately 30µm in diameter is typically measured for ease of positioning. Since a measuring area of ordinary spectrophotometer is approximately 3mm in diameter, the light intensity in a microscopic spectrophotometer is only approximately 100ppm, by an abridged calculation. In addition, this is not limited to microscopic, the band width measured by a spectrophotometer is approximately 3nm of half maximum full-width from the visible wavelength range of 380–780nm, making the light intensity 1% or less, by a simple calculation. As in the above, there is the adverse condition of the light intensity for measuring the colors in each of the color filter pixels being very small. In order to gain a little bit of light intensity, it is desirable to use an objective lens that has a large NA.

Although spherical aberration due to cover glass may sound strange, spherical aberration arises for converging or diverging rays, even if the surfaces of the glass are ideally flat and parallel. Setting aside is spherical aberration, when an object is placed close to the lens like that in a microscope, the aberration by a parallel plate such as cover glass appears, and objective lenses are designed on the premise of the use of the JIS standard cover glass[25), 26)]. Therefore, the image can deteriorate when the specified cover glass is not used. The larger the NA of the lens is, the greater the deterioration. Since, in addition to the light intensity being extremely low, there is the cover glass problem, sufficient calibration and maintenance are necessary. A convenient method of calibration and inspection of spectrophotometers is to measure plural colored glass filters and optical crystals[27)–29)]. Some of the abridged microscopic spectrophotometers have optical fibers as the parts of the optical system. It is not so significant for single mode fibers, but light leaks occur easily in multimode optical fibers (these are the ordinary ones), and this is affected not only by any change in the curvature of the assembled fiber, but also by temperature and vibration. Since the amount of light leakage varies with the wavelength, it is literally an abridged type.

By the way, the smaller the curvature of the lens is, the smaller the spherical aberration. Therefore, a lens with higher index material and smaller curvature have less spherical aberration compared with a lens having lower index and same focal length. It is difficult to make a lens with diamond which refractive index is highest, so a lens having short focal length is made by assembling plural lenses having small curvatures and long focal lengths26). The limit of smaller curvature is plain parallel plate such as cover glass, but when converging or diverging angles of incident light is large (corresponding to high NA lens), spherical aberration remains. Coupling many lenses is effective for correcting aberrations, but convex and concave lenses must be combined for correcting chromatic aberration. As can be seen in an anatomical chart, the human eye is a combination of convex lenses. Therefore, chromatic aberration is not corrected, and the situation becomes very sever. And the magnitude between red (700nm) and blue (400nm) is approximately 2.0 diopters 31). If you try on a set of reading glasses, like those found at optician's shops or bookstores, which are marked +2 (meaning a convex lens with focal length of 1/2 m, +2 diopters), it is easy to understand the extent of 2 diopters.

Conclusion

We have worked at in increasing the efficiency of the development of materials related to color filters by improving the technological outlook using optical considerations and basic data. We have introduced a part of this above. Just as the existence of electromagnetic wave is foreseen by Maxwell's equations on electromagnetic field, an improved technological outlook and knowledge leading to predictions are important. We would like to continue the efforts mentioned above.

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PROFILE

Kiyoharu NAKATSUKA

Sumitomo Chemical Co., Ltd.
IT-Related Chemicals Research Laboratory
Research Fellow