A new backlighting system using a polarizing light pipe

by H. Tanase
J. Mamiya
M. Suzuki

A new backlight with a polarizing light pipe that has great potential for improving the light yield of a liquid crystal display (LCD) is being developed. The aim is to eliminate the three major absorption losses of a TN LCD, which occur in the dichroic polarizer attached to the thin-film-transistor (TFT) glass, the black matrix on the TFT glass, and the color-filter array. The loss in the dichroic polarizer is reduced by the use of a backlight with a polarizing light pipe which produces linearly polarized light output. Both by theory and by experiment we have shown that the polarizing light pipe produces highly polarized light output under optimum conditions, i.e., a 17:1 polarization ratio in the viewing range from −10° to 10°. The brightness gain by polarization is calculated to be 1.44. The losses in the black matrix on the TFT glass and the absorbing color filter are reduced by making these components reflective, so that the light which was previously absorbed is now reflected back into the backlight for recycling. The backlight with a polarizing light pipe is effective in reusing the reflected light. When a reflective color filter is used, the brightness gain of a backlight with a polarizing light pipe over a conventional backlight is 11.3%. The total potential brightness gain by this method of light recycling is theoretically estimated to be 3.16. Therefore, the total gain of an LCD using a polarizing light pipe and reflective components over a conventional LCD is 4.55. This large gain suggests great potential for the polarizing light pipe.

Introduction

A thin-film-transistor liquid crystal display (TFT/LCD), in general use for notebook computers, has a structure similar to that shown in **Figure 1**. Major components of interest are the backlight, the thin-film-transistor (TFT) glass, the color-filter glass, and the two dichroic polarizers attached to the color-filter glass and the TFT glass.

The backlight is the light source for an LCD system. It consists of an acrylic light pipe with diffusive dots printed on its rear face, a lamp usually placed at one end of the light pipe, a reflective film on the rear face, and optical films on the front face to enhance the light output in the normal direction. Light from the lamp, which is conducted into the light pipe, travels longitudinally within the light pipe and is reflected by the diffusive dots and emitted out the front face of the pipe. The arrangement and density of the dots are controlled to achieve uniformity of light output throughout the front surface.

0018-8646/98/$5.00 © 1998 IBM

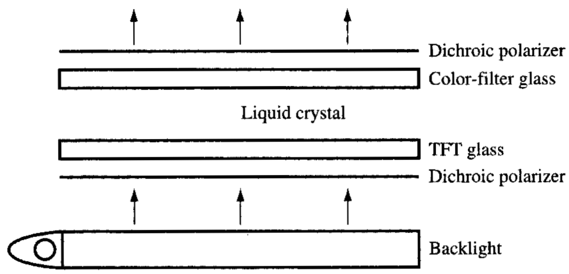

Figure 1

The main components of a TFT/LCD. Light from the backlight travels through a polarizer, TFT glass, color filter, and another polarizer.

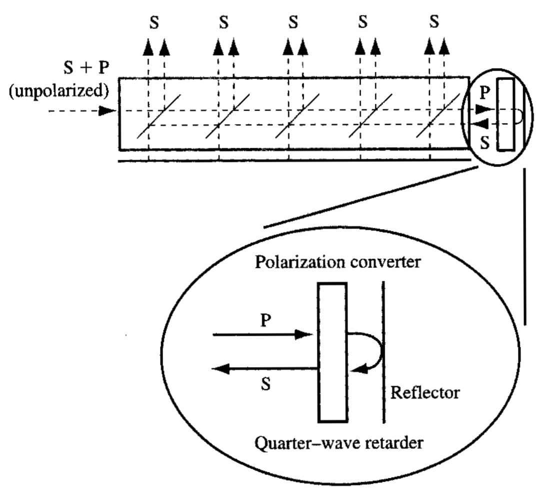

Figure 2

Schematic diagram of a backlight with a polarizing light pipe. Unpolarized light input is split into two polarization components by inclined surfaces and subsequently recycled by a polarization converter.

The TFT glass has a matrix of transparent pixel electrodes with nonactive space between them. Each of the pixel electrodes corresponds to a color filter on the color-filter substrate. The nonactive area is coated with an absorptive material, which is called the black matrix. The aperture ratio is the proportion of the sum of all of the pixel electrode areas to the total area of the TFT glass.

The color-filter glass also has a matrix of pixels. A triplet of red, green, and blue pixels forms a unit that works as a screen pixel. Each pixel on the color-filter substrate is aligned to a corresponding pixel electrode on the TFT glass.

An analysis of the structure of a TFT/LCD briefly described above reveals that it is an optically very inefficient system. For example, in a 12.1-in. SVGA panel, currently in wide use for notebook computers, a mere 10% of the total light output from the backlight eventually reaches the viewer's eye; the rest is lost along the way. There are three major absorbers. The first is the dichroic polarizer attached to the TFT glass. As the unpolarized output from the backlight passes through the polarizer, its intensity is halved owing to complete absorption of one polarization component as well as some absorption of the other component. The second absorber is the black matrix on the TFT glass, an absorptive substance coated on the non-pixel area of the TFT glass. The amount of loss by the black matrix is proportionate to the non-pixel area, or the complement of the aperture ratio of the TFT glass. Since the aperture ratios of 12.1-in. SVGA panels range around 70%, the loss is approximately 30%. The third absorber is the color filter. Although various alternative filter schemes are being developed [1–4], the method currently in general use is pigment dispersion [5]. Each pigment-dispersed pixel on the color filter transmits light in its specific wavelength range and absorbs the rest. The color-filter absorption is approximately 70%. Finally, the combination of these three major factors yields the above-mentioned low figure of 10%.

Major efforts have naturally been directed toward eliminating the loss due to the dichroic polarizer because of the large loss associated with it. One solution is to pre-polarize light coming from the backlight without losing the second polarization component, so that the amount of loss by the dichroic polarizer is reduced proportionately as the rate of polarization increases. Several types of polarizers have been developed in this approach [6–9]. They are implemented as an additional film placed on top of a conventional backlight to polarize the output. They all have a reflective mechanism by which one polarization component is transmitted and the other is reflected. The reflected component is repeatedly reused by being depolarized and sent back into the film. These films are collectively classified as reflective polarizer films.

In this paper, a new backlight with a polarizing light pipe that is aimed at reducing all three losses in a TFT/LCD is described. The loss caused by the dichroic polarizer is avoided through the use of polarized output. The losses caused by the black matrix of the TFT glass and the color filter are mitigated by modifying the TFT glass and the color filter so that they reflect the light that was previously absorbed and lost. The light reflected back toward the backlight by the now-reflective TFT glass and color filter is then reused. In the following, the polarizing capability of this new backlight is first discussed. Second, its capability to recycle the light reflected back from the modified reflective TFT glass and the color filter is described. Finally, in order to show the potential of this method, the total gain this new backlight brings to an LCD system by the above method is discussed.

Design

The new backlight with a polarizing light pipe is composed of a polarizing light pipe, a light source, a reflector film, and a polarization converter, as shown in **Figure 2**. Light entering the polarizing light pipe is split into two orthogonal polarization components: S-polarization is emitted from the light pipe, and P-polarization is transmitted through the light pipe and out of the opposite end into the polarization converter. (S-polarization and P-polarization respectively denote the polarization components perpendicular and parallel to the plane of incidence.) Subsequently, the P-polarization reaching the end of the polarization converter is converted into S-polarization and turned back into the light pipe. Re-entering the light pipe as S-polarization, this light is reflected by the inclined surfaces and the mirror at the bottom of the light pipe and is emitted as S-polarization. Therefore, this backlight with a polarizing light pipe emits all of the light entering it as S-polarization by this two-step polarization-splitting and -recycling mechanism.

- *Separating polarization components*

The polarizing light pipe uses Brewster's angle to separate the polarization components of the input light. Noting the fact that at Brewster's angle the reflectance of P-polarization becomes zero, a series of inclined surfaces built inside the polarizing light pipe whose angle of inclination to the normal incidence approximates Brewster's angle can be made to work as polarization splitters. Therefore, only the S-polarized component of the input light is reflected and emitted from the light pipe as it traverses the light pipe, and the P-polarized component is transmitted through the light pipe and out of the opposite end.

The actual angle of inclination of the internal surfaces is, in our primary design, set to be 45°. This is because Brewster's angle is approximately 45° when the refractive indices of the two media that constitute the boundary surface are sufficiently close to each other. Thus, the refractive indices of the composing materials have to be sufficiently close to each other to ensure the polarization-splitting capability of the 45° inclined surfaces.

There are various methods that can achieve internally formed inclined surfaces in a polarizing light pipe. One method is to stack thin slanted plates with transparent adhesive between them to form a block with a series of plates inclined 45° to the face of incidence. Another method is to laminate two prismatic films on their face of prismatic construction with adhesive between them. This method will create a polarizing light pipe with internal surfaces inclined 45° alternately toward and away from the input face (**Figure 3**). In this paper, this construction, called a *coupled prismatic-polarizer light pipe*, is the main focus.

Figure 3

Coupled prismatic polarizing light pipe, showing one method of forming inclined surfaces inside the light pipe.

- *Recycling the parallel polarization*

P-polarization transmitted out of the light pipe is converted into S-polarization by a polarization converter placed at the end opposite to the input face. The polarization converter consists of a quarter-wave retarder and a reflector. The axis of the quarter-wave retarder is either parallel or perpendicular to the illuminating face. Light entering this unit passes through the quarter-wave retarder twice, as shown in Figure 2. Therefore, linearly polarized light whose plane of polarization is either parallel or perpendicular to the illuminating face has its plane of polarization rotated by 90° by this polarization converter. In our design, P-polarization transmitted out of the light pipe is converted into S-polarization by this unit and turned back into the light pipe to be recycled.

The recycling efficiency of the polarization converter is determined by the efficiency of the quarter-wave retarder and the transmittance of light at the end face of the light pipe. The typical wide-bandwidth quarter-wave retarder available at present has an efficiency of approximately 75%. The transmittance at the end face of a light pipe is 96%. Therefore, the efficiency of the polarizer converter is calculated to be 69%.

- *Output uniformity*

With the construction described thus far, the output luminance in the direction normal to the direction of input will be a concave curve with a low center. The luminance will be the lowest at the center of the light pipe and will increase in either direction toward the ends. In order to correct this gradation in luminance, the reflectance at the inclined surfaces must be altered

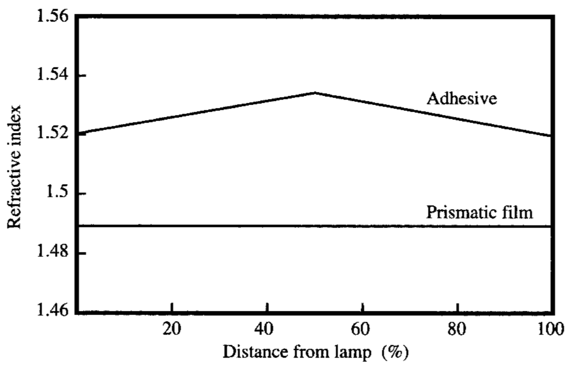

Figure 4

Gradation in refractive indices of adhesive and prismatic film. The refractive index of the adhesive is linearly altered from 1.520 at either end to 1.535 at the midpoint.

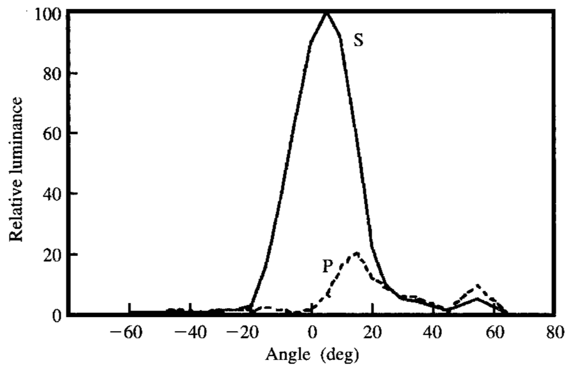

Figure 6

Output distribution of a coupled prismatic-polarizer light pipe. (Computer simulation; input = $\pm 20°$, gap-width ratio = 1:100.)

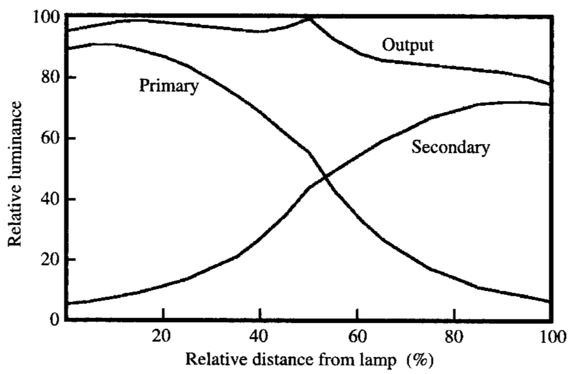

Figure 5

Scan of light output in the direction perpendicular to the input face. Light output is made uniform by a method of linear gradation in the refractive index of the adhesive.

depending upon their location within the light pipe. There are two possible methods:

1. Create a gradation in density of surfaces.
2. Create a gradation in refractive index of the adhesive.

One or both can be applicable, depending on the type of polarizing light pipe. To the coupled prismatic-polarizer light pipe, only the second method can be applied.

Here it is noted that the output is the sum of light reflected by the surfaces in the first pass, called primary output for convenience, and light that has reached the end of the light pipe and been turned back into the light pipe by the polarization converter, called secondary output. It then follows that the reflectance should be the greatest in the middle and should decrease in either direction toward the two ends of the light pipe.

As an example, method 2 is applied to a coupled prismatic-polarizer light pipe. The number of total prisms (microprismatic columns that are approximately 100 μm in size) in the light pipe is assumed to be 2000. The refractive index of the composing prismatic films is 1.49, and the refractive index of the adhesive has a linear gradation starting from 1.520 at either end and increasing to 1.535 at the midpoint of the light pipe (**Figure 4**). With this configuration, the output in the normal direction forms the curve depicted in the graph shown in **Figure 5**. This output satisfies a uniformity condition in which the luminance is highest at the midpoint and the lowest luminance at either endpoint is no less than 80% of the highest luminance.

Polarizing capability (theoretical evaluation)

The polarizing capability of the polarizing light pipe has been studied by computer simulation. The rate of polarization together with the efficiency of the polarization converter determines the increase in light output.

The computer simulator used here executes ray tracing based on two-dimensional geometrical optics. Reflection and transmission at the boundaries are assumed to be ideally specular. The specific dimensions and configuration of the polarizer light can be input to the simulator for calculation.

• *Results*
The coupled prismatic-polarizer light pipe was selected for evaluation. The following two influential parameters were selected to see their effects on the output distribution:

- Angular breadth of input.
- Gap-width ratio (ratio of the thickness of the adhesive layer between the pair of prismatic films to the height of the prisms).

The first is related to the extent of collimation of the input beam, and the second is related to the degree of adhesion between the two prismatic films.

Figures 6–8 show the output distributions computed by the simulator under three different conditions.

• *Discussion*
Figure 6 shows the result using a ±20° input distribution and a gap-width ratio of 1:100. The graph shows a very highly polarized output that has a sharp peak near the normal direction. The polarization ratio is 17:1 in the −10° to 10° range and 8:1 in the −20° to 20° range. This result gives strong evidence of the high polarizing capability of the polarizing light pipe. The increase in light use in this case, taking into consideration the efficiency of the polarization converter, is 1.44. On the other hand, the subsequent two graphs under different conditions (either larger angular breadth of input or thicker gap width) show degraded output distribution marked by dull peaks of S-polarization and profuse emission of P-polarization in off-angle directions (**Figure 7** and **Figure 8**).

In the first result (Figure 6), aside from its highly polarized and localized profile, a few points can be observed. The peak of S-polarization is 5° off the normal direction. P-polarization has a small peak, about one-fifth the peak of S-polarization, at 15° off normal, and in the higher angular range the emission is contained within a low limit.

In the second result, under the condition of broadened input beam and narrow gap width (Figure 7), the luminance peaks of both S-polarization and P-polarization fall 35° off the normal direction. The distributions of the two polarizations differ little for an angular range of more than 30°. The rate of polarization in the near-normal range, i.e., −10° to 10°, is fair but the intensity in that range is outweighed by the presence of a much stronger peak in the 30° off-normal direction. The rate of polarization in the total angular range is low.

In the third result, under the condition of collimated input beam and wider gap width (Figure 8), a broadened distribution of S-polarization, stretching to 40°, and an emission of P-polarization of the same order in the 20°–40° range is observed. The S-polarization peak in the normal direction is strong, but the amount of

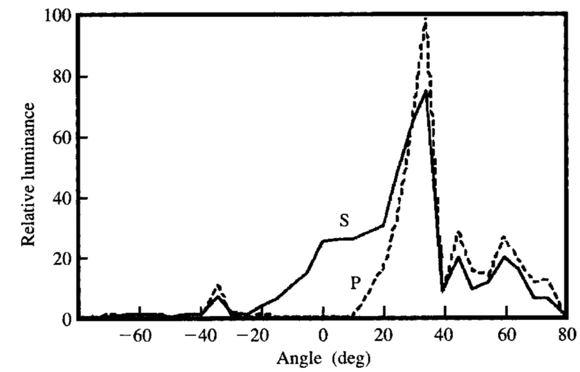

Figure 7

Output distribution of a coupled prismatic-polarizer light pipe. (Computer simulation; input = ±80°, gap-width ratio = 1:100.)

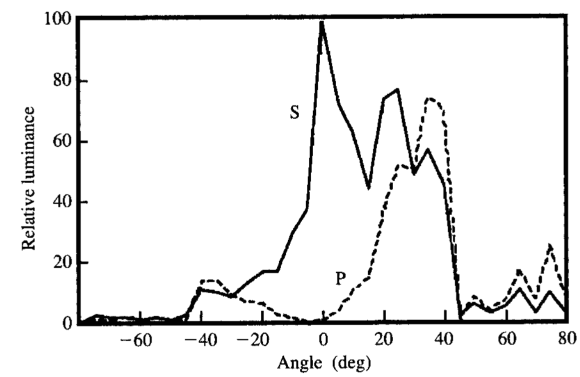

Figure 8

Output distribution of a coupled prismatic-polarizer light pipe. (Computer simulation; input = ±20°, gap-width ratio = 1:10.)

P-polarization emitted is of order comparable to that of S-polarization, leading to low polarization in a wide angular range, as in the second result.

From the three results, it can be seen that two parameters, the angular breadth of the input and the gap width, play a significant role in the output distribution. This can be understood by recalling that the polarizing light pipe is designed to work optimally with light parallel to the plane of the light pipe. Therefore, the more the direction of a ray traversing the light pipe deviates from the direction parallel to the light pipe, the farther from the normal direction the ray will be emitted, and the less the rate of polarization will be. Given these

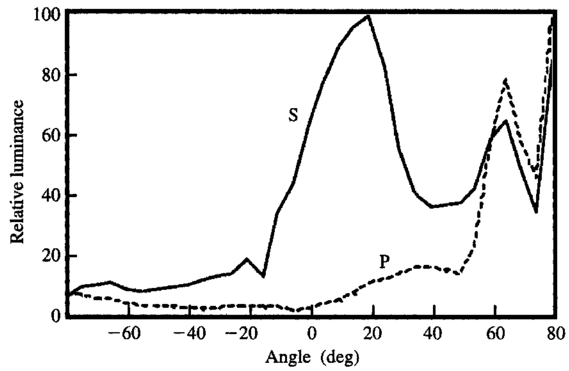

Figure 9

Output distribution of a coupled prismatic-polarizer light pipe. (Single-layered sample; laser input.)

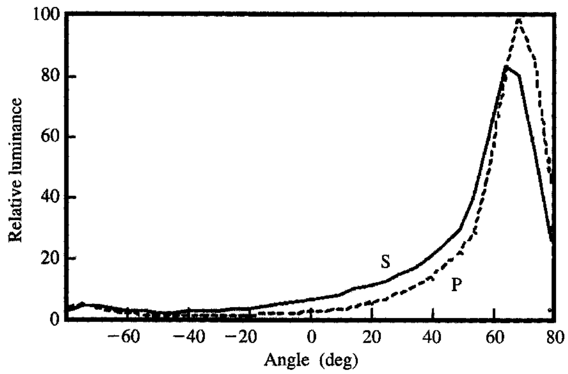

Figure 10

Output distribution of a coupled prismatic-polarizer light pipe. (Multilayered sample; laser input.)

characteristics, it becomes evident that collimated input is better than noncollimated input. On the other hand, the gap width affects the course of the rays traveling in the light pipe as the region near the vertex of the prism deflects light. A wider gap means a larger area at the tip of the prism, where light is deflected.

Polarizing capability (experimental evaluation)

• *Samples*

The polarization capability of the polarizing light pipe has also been studied by testing actual samples. From the possible constructions, the coupled prismatic structure was selected. The coupled prismatic samples were built by bonding a pair of prismatic films on the faces on which the prismatic columns are formed with a thin layer of transparent adhesive. Each pair of prismatic films adhered in this fashion forms a single-layered unit. Multilayered samples were built by stacking single-layered units.

The structural and optical parameters were determined as dictated by the design of the polarizing light pipe discussed earlier. The vertex angle of the prism was set to be 90°, and the refractive indices of the prismatic films and the adhesive were selected to be sufficiently close to each other.

Some of the difficulties faced in building such samples are selecting materials that have both manufacturability and a low internal absorption rate, preventing sample degradation due to excessive exposure to light, and avoiding the formation of minute bubbles in the samples.

• *Results*

The graphs in **Figure 9** and **Figure 10** are the output distributions of a single-layered sample and a ten-layered sample with a laser used as input. The measured values are rescaled to make the maximum point equal to 100.

• *Discussion*

The output distribution of the single-layered sample shows a high degree of polarization and a sharply localized peak in the near-normal direction, giving a strong endorsement to the polarizing capability of the polarizing light pipe. The polarization ratio is 20:1 in the −10° to 10° range. The overall distribution is similar to the distribution calculated by computer simulation under the conditions of collimated input and narrow gap width (Figure 6). One difference, however, is the existence of off-normal emission at 65°.

On the other hand, the output distribution of the multilayered sample is marked with an extremely intense peak in the 70° off-angle direction. This strong off-angle emission overshadows the locally polarized output near the normal direction and brings the overall rate of polarization to a negligible level.

Internal sway-angle model

In order to understand the output distribution of the samples, a model that extracts the functional core of the polarizing light pipe has been designed. It makes use of the fact that the output light is primarily, to a first-order approximation, a superposition of rays reflected by an internal surface, where the pair of surfaces on either side of the adhesive layer are regarded as a single surface having the combined reflectance of the two (**Figure 11**). Then the distribution of light within the light pipe, termed internal distribution, can be linked to the output distribution by a one-to-one mapping. The internal distribution is computed from the output distribution by the following formula:

$$d_{in} = [d_{out}/(tc^{-1})]c, \quad (1)$$

where

d_{in} = internal distribution,
d_{out} = output distribution,
c = mapping from the internal sway angle to the output angle,
t = the rate of light transmission from the light pipe following the path in Figure 11.

By applying this model to the measured output distribution of the samples and plotting the internal light distribution, it is observed, as seen in **Figure 12**, that the direct cause of off-angle output emission is the existence of internal light in the range exceeding a certain angle. As we note that the internal distribution and the output distribution are linked by a one-to-one mapping, light going out in a particular off-normal direction is due and due only to the existence of internal light incident upon the inclined surface at a corresponding angle, the sway angle. Thus, eliminating off-angle emission is tantamount to eliminating swayed light within the light pipe. Possible causes for light swaying inside the light pipe can be grouped into two categories, deflection and diffusion. Deflection is caused by neighboring regions of prism vertices. As was discussed earlier in relation to the results from computer simulation, deflection increases with any increase in the thickness of the adhesive layer. In actual samples, rounding of the vertices of the prisms also increases the degree of deflection. These causes of deflection can be reduced by improving the quality of the samples. On the other hand, diffusion is caused by rough surfaces. A ray transmitted through a rough surface turns into a broadened distribution with a decreased peak in the original direction. Therefore, successive rough surfaces as in a coupled prismatic-polarizer light pipe can sway an originally collimated laser input.

In the present samples, examined by computer simulation, diffusion is thought to be the dominant cause of sway. This also explains why multilayered samples perform less well than single-layered samples, because in multilayered samples the rays have to pass more surfaces before being emitted from the light pipe.

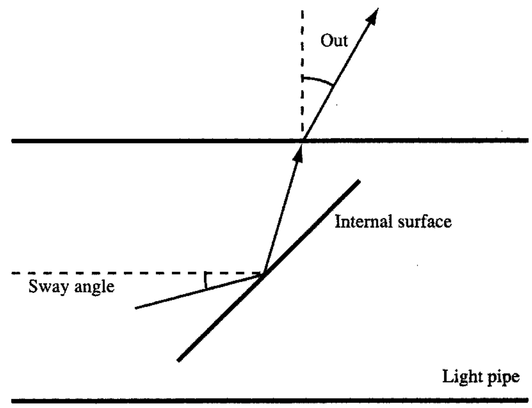

Figure 11

Model of the polarizing light pipe. In this model, the output is considered to result from an internal light distribution hitting an inclined surface. The output and the internal distribution are linked by a one-to-one mapping.

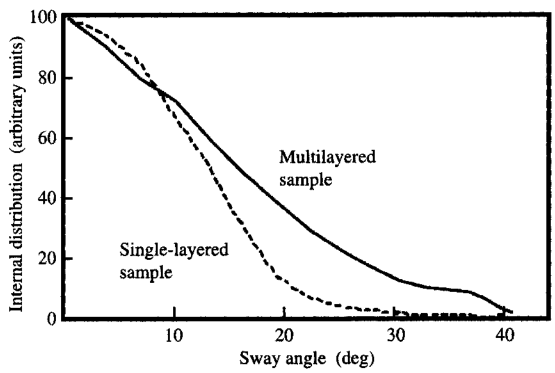

Figure 12

Internal distributions of the single-layered sample and the multilayered sample. The distribution of the multilayered sample is much broader, showing evidence of strong off-angle emission.

Recycling light reflected from the TFT glass and the color filter

Light output from the backlight, after it passes through the polarizer, is partially absorbed by the black matrix of the TFT glass, and then by the pixel areas of the color filter. The loss created by the black matrix of the TFT glass is the ratio of the area of the black matrix to the total area of the glass, which is 100 minus the aperture ratio, and is typically 30% in current TFT/LCDs used for notebook computers. The loss by the color filter is due to the nature of the pigments used for the red, green, and blue (RGB) pixels. Pigment-dispersed pixels transmit light in a specific wavelength range and absorb the rest, resulting in a 30% light use (a 70% loss).

The loss can be reduced by making the TFT glass and the color filter reflective. A reflective substance, such as aluminum, may be coated on the area of the black matrix, and a patterned dichroic mirror consisting of red, green,

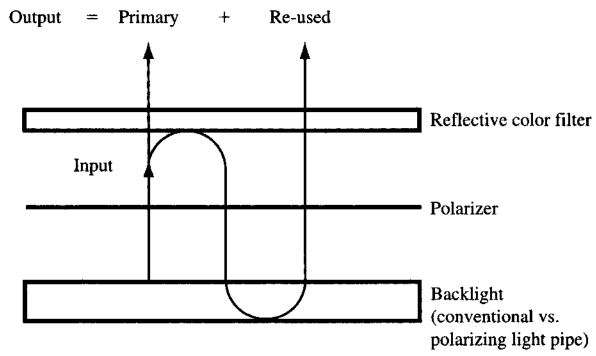

Figure 13

Schematic of experiment. The light-recycling capability of the polarizing light pipe is investigated using a reflective color filter.

and blue dichroic mirrors may be used in place of a dye color filter [2]. With this new structure, light which was previously absorbed is now reflected back toward the backlight and recycled. The effectiveness of the polarizing light pipe in recycling this reflected light is explored in the following sections.

• *Result*

The advantage of the new backlight with a polarizing light pipe over a conventional backlight in recycling reflected light from a reflective TFT glass and a reflective color filter has been studied by experiment. For the experiment, a simplified model of an LCD consisting of a backlight, a polarizer, and a reflective color filter was used (**Figure 13**). The TFT glass was omitted in this model. After installation of the two backlights, for each setting, their light outputs with and without the reflective color filter, defined as output and input, respectively, were measured. Next, the transmittance of the system was defined as a quotient of output over input. It was used as a relative index of the degree of light recycling. **Table 1** shows the transmittance of the two systems calculated from measured input and output.

• *Discussion*

The experiment showed that the polarizing light pipe is 11.3% more efficient than a conventional backlight in recycling reflected light from a reflective color filter. One reason for this is that the polarizing light pipe has a high transmittance in the normal direction; therefore, much of the light coming into the backlight is reflected back for recycling toward the TFT and the color-filter glass. Another reason is that it does not depolarize light traveling in the normal direction, while a conventional backlight has depolarizing agents such as a diffuser film and diffusive dots printed on the rear surface of the light pipe. In the presence of a polarizer, this is an important factor because depolarized light is absorbed by the polarizer on its way toward the TFT and the color filter glass.

A theoretical estimate can be made of the light-recycling potential of this LCD system equipped with a reflective TFT glass and a reflective color filter. Assumptions for the derivation of Equation (2) are the following:

- The black matrix reflects r_{BM} of light, and $(1 - r_{BM})$ of light is lost.
- The color filter reflects r_{CF} of light.
- The polarizer light pipe recycles e_{PLP} of light and loses $(1 - e_{PLP})$ of light.

Then the increase in transmittance, represented as a ratio of the transmittance when both the black matrix of the TFT glass and the color filter are ideally absorptive, is given by the following series:

$$gain_{\text{recycle}} = \sum_{n=0}^{\infty} e_{PLP}[(1-a)r_{BM} + ar_{CF})]^n, \tag{2}$$

where

a = aperture ratio of the TFT glass,
r_{BM} = reflectance of the non-openings (black matrix in a conventional TFT glass) of the TFT glass,
r_{CF} = reflectance of the color filter,
e_{PLP} = rate of light recycled by the polarizing light pipe.

Substituting a few combinations of specific values produces **Table 2**.

Total gain in light use

The potential total gain in light use by a TFT/LCD consisting of the new backlight with a polarizing light pipe and the reflective TFT glass and color filter has been investigated theoretically. Two sources of gain are reduction in loss by the dichroic polarizer and recycled light previously absorbed by the black matrix of the TFT glass and by the color filter. Each gain is described below.

• *Gain from polarization*

This gain, from use of the polarization component that is lost in a conventional, nonpolarizing backlight, is expressed by the following formula:

$$gain_{\text{pol}} = \left(\frac{S}{S+P}\right)(1 + e_{\text{recycle}}) = \frac{5.8}{5.8+1}(1 + 0.69) = 1.49, \tag{3}$$

where

S, P = emitted S- and P-polarization, respectively. $S:P$ = 5.8:1 (calculated from the result shown in Figure 6);

e_{recycle} = efficiency of the polarization converter.

The ratio $S:P$ is calculated as 5.8:1 from the result shown in Figure 6, and e_{recycle} is calculated as 69% from information in the section which discusses the polarization converter.

- *Gain from light recycling*

A theoretical estimate of this gain is expressed by Equation (2). Substituting the second set of values in Table 2 for the variables gives the following:

$$gain_{\text{recycle}} = 3.16. \tag{4}$$

- *Total gain*

The total gain is found by multiplying the results of Equations (2) and (3):

$$gain_{\text{total}} = gain_{\text{pol}} \cdot gain_{\text{recycle}} = 4.55. \tag{5}$$

Table 1 Transmittance measured using the scheme shown in Figure 13.

	Transmittance (= output/input) (%)
Conventional backlight + reflective color filter	23.9
Polarizer light pipe + reflective color filter	26.6

Table 2 Increase in transmittance of a system with a polarizing light pipe. A smaller aperture and better recycling capability in the polarizing light pipe increase the gain.

Condition	*Increase in transmittance (%)*
$a = 50\%, r_{\text{BM}} = 90\%, r_{\text{CF}} = 70\%, e_{\text{PLP}} = 90\%$	3.57
$a = 70\%, r_{\text{BM}} = 90\%, r_{\text{CF}} = 70\%, e_{\text{PLP}} = 90\%$	3.16
$a = 50\%, r_{\text{BM}} = 90\%, r_{\text{CF}} = 70\%, e_{\text{PLP}} = 50\%$	1.67

Conclusion

In this paper, a new backlighting system that uses a polarizing light pipe has been described. This backlight is capable of addressing the major causes of absorption loss in an LCD. The losses occur at the dichroic polarizer, the black matrix of the TFT glass, and the color filter.

The 50% loss at the dichroic polarizer is minimized by producing linearly polarized output from the backlight. The absorption decreases as the degree of polarization of the output from the backlight increases. The polarizing capability of the polarizing light pipe has been studied both theoretically by computer simulation and experimentally by actual measurement of samples.

A theoretical study by computer simulation showed that the polarizing light pipe is capable of producing highly polarized output (17:1 polarization ratio in the range from $-10°$ to $10°$ in the normal direction under optimal conditions. The desired conditions include collimated input and narrow gap width. The output distribution degenerates as the conditions deviate from the optimal.

Actual measurements of samples give strong support for the polarizing capability of the polarizer light pipe. Single-layered samples produced a 20:1 polarization ratio in the range from $-10°$ to $10°$ with a collimated light. Off-angle emission in single-layered samples was greater than predicted by theory but of moderate intensity. Multilayered samples, however, produced completely unexpected output, which was marked by extremely intense off-angle emission and an overall low polarization rate. From study of a model (the sway-angle model), the moderate off-angle emission in single-layered samples and the extreme one in multilayered samples were both attributed primarily to diffusion at internal inclined surfaces.

The absorption of the black matrix of the TFT glass and the color filter was shown to be reduced by making those components reflective and letting the reflected light be recycled. The polarizing light pipe was shown to be more effective than a conventional backlight in recycling the reflected light, as it has a higher transmittance in the normal direction and is free of diffusive elements that hinder light recycling in the presence of a polarizer. The gain in transmittance in a simple scheme was investigated in comparison with a conventional backlight. The measured gain was 11.3%.

Finally, the potential of this new backlight was evaluated by determining the potential gain it can bring to an LCD as a whole. As a multiplication of the gain by polarization and the gain by light recycling with a reflective TFT glass and color filter, it was calculated to be 4.55.

Directions for future study

The problems of present samples have been analyzed, and a major culprit is found to be diffusion. Efforts should therefore now be directed to creating surfaces that are specular and free of diffusion. As the performance of samples improves, their output should be more precisely compared with computer simulation results.

The effect of input should be investigated. Instead of using as input a laser, which is an ideally collimated input, a lamp with a reflector such as that used in existing backlights should be tried. Methods of collimating output from a lamp should also be explored.

The study of the capability of the polarizing light pipe to recycle light reflected back from the TFT glass and the color-filter unit should be further developed. Experiments and analyses to explain the discrepancy between measurement and calculation should be carried out.

Acknowledgments

The polarizing light pipe was developed jointly with Sekisui Chemical Corporation. The authors thank Hiroyuki Nakatani, Tsuyonobu Hatazawa, and Takashi Watanabe for their continuous efforts to build better samples and also for their extended contributions to design and theory. The authors also thank Takeshi Inoue and Hiroshi Ogawara for organizing and sustaining the project.

References

1. S.-F. Chen and H.-P. D. Shieh, "Design Issues in Using Thin-Film Optical Interference Filters as Color Filters for LCD System Applications," *Digest of Technical Papers*, Society for Information Display International Symposium, 1994, pp. 411–416.
2. Fu-Jen Ko, Jinn-Chou Yoo, and Han-Ping D. Shieh, "High Efficiency Color Filter for LC Projection System Applications," *Proceedings of Euro Display '96* (Society for Information Display) 1996, pp. 529–532.
3. R. Maurer, F.-H. Kreuzer, and J. Stohrer, "Cholesteric Reflectors with a Color Pattern," *Digest of Technical Papers*, Society for Information Display International Symposium, 1994, pp. 399–402.
4. J. Biles, "Holographic Color Filters for LCDs," *Ibid.*, pp. 403–406.
5. Takeo Sugiura, "Development of Pigment-Dispersed-Type Color Filter for LCDs," *J. SID* **1/3**, 341–346 (1993).
6. D. J. Broer, J. A. M. M. van Haaren, G. N. Mol, and F. Leenhouts, "Reflective Cholesteric Polariser Improving the Light Yield of Back- and Side-Lighted Flat Panel Liquid Crystal Displays," *Proceedings of Asia Display '95* (Society for Information Display), 1995, pp. 735–738.
7. D. Coates, M. J. Goulding, S. Greenfield, J. M. W. Hanmer, E. Jolliffe, S. A. Marden, O. L. Parri, and M. Verrall, "New Applications of Liquid Crystals and Liquid Crystal Polymers," *Proceedings of Euro Display '96* (Society for Information Display), 1996, pp. 91–94.
8. M. F. Weber, "Retroreflective Sheet Polarizer," *Digest of Technical Papers*, Society for Information Display International Symposium, 1992, pp. 427–429.
9. T. Gunjima, M. Ozeki, and Y. Ooi, "New Back-Lighting Device for Liquid Crystal Displays," *Proceedings of Asia Display '95* (Society for Information Display), 1995, pp. 731–734.

Received March 17, 1997; accepted for publication December 31, 1997

Hiroshi Tanase *IBM Japan Ltd., Display Technology, Display Business Unit, 1623-14 Shimotsuruma, Yamato-shi, Kanagawa-ken 242, Japan (tanase@jp.ibm.com).* Mr. Tanase spent the year 1991–1992 at the University of Wisconsin as a Rotary Scholar. He received his B.S. in physics from the University of Tokyo in 1994, joining IBM the following year. In 1996, Mr. Tanase received his first patent award. Since joining IBM, he has worked on developing new backlight technologies and has also developed backlights for specific IBM LCD products. His current interests are in technologies to make backlights thinner and smaller.

Johji Mamiya *IBM Japan Ltd., Display Technology, Display Business Unit, 1623-14 Shimotsuruma, Yamato-shi, Kanagawa-ken 242, Japan (jl17038@jp.ibm.com).* At Waseda University in Japan, Mr. Mamiya majored in electronic communications, studying the impulse response of the human acoustic organs. As a chief engineer and subsequently a working manager at IBM, he has worked on the development of graphics chips and on desktop, portable, and notebook PC systems. Since joining the Display Technology Department in 1993, he has designed a 16-in. TFT demonstration model and has worked as backlight group manager for two years.

Masaru Suzuki *IBM Japan Ltd., Display Technology, Display Business Unit, 1623-14 Shimotsuruma, Yamato-shi, Kanagawa-ken 242, Japan (suzki@jp.ibm.com).* Mr. Suzuki received his B.S. in mechanical engineering from the University of Tokyo in 1985, joining IBM that same year. After two years with the IBM Storage Products Division, he has been in charge of the development of liquid crystal display modules in the IBM Display Business Unit for more than ten years. His major area of interest is optical design of backlighting units for liquid crystal displays. Mr. Suzuki received the Best Poster Paper Award from the Society for Information Display in 1996. He received an IBM Corporate Award in 1997 and IBM Invention Achievement Awards in 1995 and 1997.