

Cholesteric Color Filters – Optical Characteristics, Light Recycling and Brightness Enhancement

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Abstract

We demonstrate for the first time a color filter system, based on reflective cholesteric polymers, which has no major absorptive components. We report the principles of operation, process outline, optical properties, color coordinates, extinction curves, evidence for light recycling, brightness enhancement and related issues.

Introduction

The current TN LCD technology allows transmission of only about 4-6% of the light generated by the backlight (BL). Most of the loss is due to absorptive linear polarizers and color filters (CF) as well as restricted apertures. Such low efficiency is a burden on the electrical power supply, limits mobility and precludes outdoor viewing applications. Systems with higher light throughput efficiencies were developed or suggested. The most common schemes are: color separation filters and beam splitters (projection systems), reflective mirrors with large aperture ratio (DMD), diffraction gratings (micro-displays) or reflective interference filters. These schemes are either too costly or not applicable to direct-view LCDs.

This state of the art provides an incentive for a low cost alternative to the current use of absorptive CFs and polarizers. We demonstrated the use of reflective cholesteric CFs as a low-loss alternative which is potentially low cost, can be integrated with current LCD technology and in combination with a broad-band polarizer⁽¹⁾ (BBP) can improve substantially the brightness of LC displays. The availability of cholesteric polymer materials and recently discovered methods^(1,2) for substantial broadening of their reflection bands made this alternative approach feasible.

Thermotropic cholesterics have a periodic structure characterized by a pitch P_0 along a helical axis. The molecular average direction rotates smoothly at a constant rate of $2\pi/P_0$ along this axis. In our application P_0 is of the order of visible light wavelengths. A right-hand (RH) cholesteric reflects the RH circular polarization component of the incident light within a given reflection band. The peak of the reflection band is given by $\lambda_0 = nP_0$

and its width by $\Delta\lambda = \Delta n P_0$ (assuming thickness $\gg P_0$). $\Delta n \approx 0.15$ is a typical value for the birefringence and $n \approx 1.6$ is an average index for light propagating along the helical axis. Outside the reflection band the cholesteric has a strong optical activity.

Polymeric LCs are distinguished by their ability to lock in, through the polymerization process, orientational configurations which are not feasible in the liquid state. In particular, it was shown recently^(1,2) that a pitch gradient configuration can be created in cholesteric polymers where the pitch value varies smoothly from one side of the layer to the other. In contrast, a stable pitch gradient in thermotropic cholesterics requires a constant external stimulus like a thermal gradient. The reflection bandwidth of a cholesteric layer with a pitch gradient structure can be much wider than the above value of $\Delta\lambda$ for a constant pitch- P_0 system. Extreme examples where the reflection band was stretched to cover the visible and the near IR wavelengths were demonstrated recently^(1,2). The pitch gradient structure forms the basis for the BBP: a broad band reflective polarizer. BBP reflects circularly polarized light, of the same handedness as that of the cholesteric material, throughout the visible while transmitting the opposite polarization. Since it acts as a no-loss reflective polarizer, BBP makes it possible to recycle the reflected light back into the display after being randomized by various reflective diffusive surfaces in the back light (BL).

The bandwidth of a constant pitch cholesteric is inadequate for CF applications. For $\lambda_0 = 550 \text{ nm}$ the bandwidth is typically $\Delta\lambda \approx 50 \text{ nm}$, which is too narrow for CFs in the visible ($\Delta\lambda \approx 400 \text{ nm}$). This shortcoming demonstrates the need for pitch gradient structures in CFs applications.

Principles of operation

A complete reflective cholesteric CF⁽³⁾ system is made of three principal layers. The first one, BBP, is positioned between the BL and the display. This component transmits only one circular polarization and recycles the opposite one thus increasing the useful radiation by about 80%. We'll assume here a RH BBP which reflects RH polarization (RHP) and transmits LHP. The second layer is a pixelated RGB cholesteric layer (Fig. 1) made of semi-

broadened LH cholesteric pixels that provide the color selectivity. For example, a Red pixel transmits LH Red light but reflects (and recycles) the LH Green & Blue components.

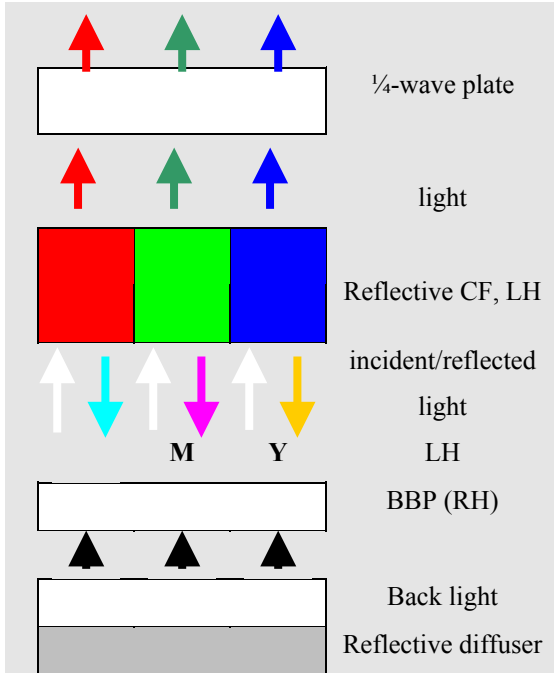


Figure 1. Structure of a reflective cholesteric CF.

The third layer is a $\frac{1}{4}$ -waveplate which transforms the transmitted LHP back into linear polarization. The last two layers reside on the internal surface of the display's rear glass. The cholesteric CF includes also a black matrix (BM) grid made of a highly reflective metal which also participates in light recycling. A top view of a complete CF is shown in Fig. 2. Pixel size is $100 \times 300 \mu\text{m}$.

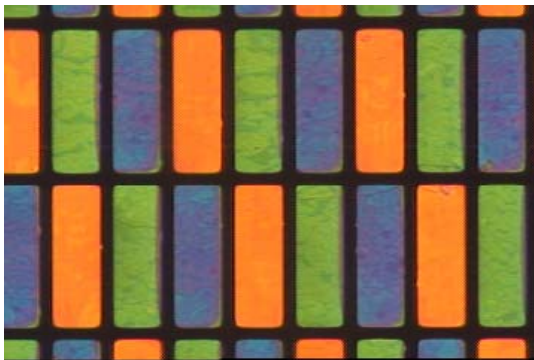


Figure 2. Front view of a cholesteric CF.

In the absence of any absorption a light recycling system is highly efficient irrespective of the aperture ratio. Real systems, however, possess residual absorption. Since this is a multi-pass

system, the cumulative effective absorption can be significantly higher than in single-pass systems. We measured a 46% transmission efficiency at normal incident for our initial prototypes.

Process

A glass substrate is coated first with a grid made of highly reflective metallic film that serves as a black-matrix (Fig. 2). Since the process starts with a cholesteric in a liquid state, standard alignment procedures apply. Color tuning of the cholesteric CF is achieved by controlling the sample temperature such that the cholesteric's narrow reflection band is centered on a desired color. The sample is then subjected to a UV curing process that broadens the reflection band as desired and freezes the cholesteric structure and its optical properties. Pixilation is achieved by proximity exposure through Cr masks.

Transmission curves and colors

The above process provides a considerable latitude in tailoring of the transmission curves so as to optimize the brightness (as measured by the Y values) and colors, measured by the (x,y) color coordinates. The system we report here was optimized for a C light source. For commercial backlight sources slightly different spectral characteristics are required. Fig. 3 shows typical transmission curves superimposed on the emission spectrum from a commercial BL. Insertion losses, which are absent from a CF embedded in a display, were factored out in these measurements. These values were measured on single color cells.

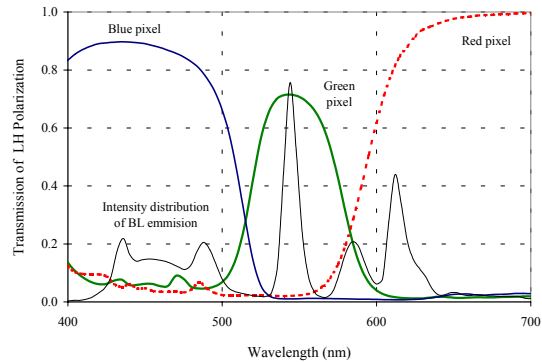


Figure 3. Typical CF transmission curves. Also shown is a typical spectrum of a commercial backlight

Fig. 4 illustrates a relatively wide color gamut spanned by the cholesteric CFs. Color coordinate values were calculated from the transmission curves assuming a C source.

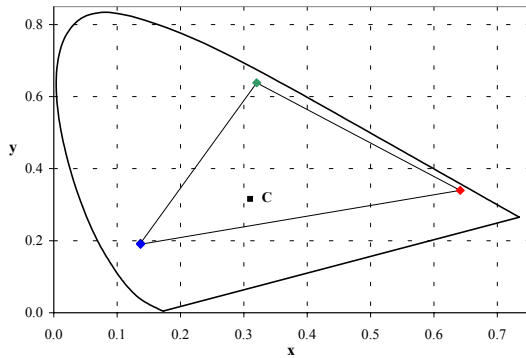


Figure 4. Color gamut in terms of CIE color coordinates (x, y)

The following table summarizes the color and transmission data.

Cell	(x, y)	Color saturation	Peak transmission
Blue	(0.137, 0.193)	76%	86%
Green	(0.320, 0.639)	87%	87%
Red	(0.642, 0.340)	95%	100%

Extinction and Brightness

Since the light exiting the CF has to be linearly polarized it is important that the cholesteric CF itself will transmit as pure a circular polarization as possible. A measure of that purity, for a LH cholesteric CF, are the extinction curves: $\text{Tr}(\text{of LH light})/\text{Tr}(\text{of RH light})$. LH (RH) polarized light was achieved by using commercial circular sheet polarizers. Examples of the measured extinction curves are shown in Fig. 5.

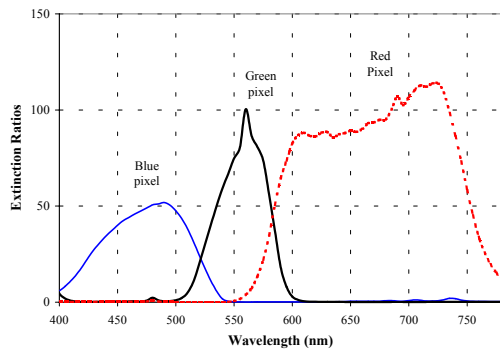


Figure 5. Extinction curves of three single color cells.

The following table illustrates the best luminance measured on our prototypes. Luminance values were calculated from the transmission data.

Cell	Luminance
Blue	27.8
Green	47.9
Red	21.3

Brightness enhancement

In order to estimate the brightness gain only due to light recycling by the BBP we measured first the luminance in the perpendicular direction from a **BL|BBP(RH)** system without a CF. The backlight consisted of a commercial light guide with only a diffuser on top. The perpendicular transmission through the BBP was above 90%, indicating that the BBP transformed, through recycling, most of the unpolarized light into a LH polarized light. For comparison, the transmission of a typical absorptive LH polarizer is about 42%. When a patterned cholesteric CF was added to the stack: **BL|BBP(RH)|Cholesteric CF(LH)**, the average transmitted luminance of five prototypes was $284 \pm 25 \text{ cd/m}^2$, equivalent to an average transmission of $T=46 \pm 4\%$. We compared the normal incidence luminance of our prototypes (aperture ratio = 73%) to a conventional absorptive color filter in the following standard configuration: **BL|Linear Polarizer|Absorptive CF** (aperture ratio = 38%). For this system we measured 35 cd/m^2 or a transmission of $T=5.8\%$. From this comparison we estimate that the average total brightness enhancement for our patterned cholesteric CFs is: 8.1 ± 0.7 . Note that for conventional absorptive CFs the light energy output is proportional to the aperture size. In contrast, in a truly lossless light-recycling system the aperture size can be varied without affecting the total light energy output. It is possible that such large enhancement factors can be maintained at lower aperture ratios by reducing the residual absorption in the CF system. This issue is under further investigation. In the current prototypes there are small absorption losses in the BL system as well as a significant loss due to a Cr black-matrix which occupies 27% of the CF area.

Reference

1. "A single-layer super broad band reflective polarizer", L. Li and M. Faris, SID96 Digest, 111.
2. "Cholesteric polarizer and manufacture thereof", Broer, J. Lub, European patent #94200026.6, 1994.
3. Patent pending.