# Bright Reflective Color Filters Based on Cholesteric Liquid Crystal Polymers

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## Abstract

We present data on a color filter system, based on reflective cholesteric polymers, which has no major absorptive components. We'll review principles of operation, process issues, optical properties, color coordinates, contrast ratios, light recycling, brightness enhancement and related issues. We'll discuss integration data of the color filter with a TFT-TN display.

## Introduction

Only about 4-6% of the light generated by the backlight (BL) reaches the user of a typical LCD based on current TN-LCD technology. Most of the loss is due to absorptive linear polarizers and color filters (CF) as well as due to 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 in the past. 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.

Such low efficiency use of the BL 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 $\Delta\lambda=\Delta nP_0$ (assuming thickness >> $P_0$). $\Delta n\approx0.15$ is a typical value for the birefringence and $n\approx1.6$ 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 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. A RH BBP reflects RH circularly polarized light throughout the visible while transmitting the opposite polarization. Since BBP acts as a no-loss reflective polarizer, it makes light recycling possible. The RH reflected light is randomized by various reflective diffusive surfaces in the backlight (BL). Half of it can now pass the BBP. In total, 80% efficiency is possible.

The bandwidth of a constant pitch cholesteric is inadequate for CF applications. For $\lambda_0$ =550 *nm* the bandwidth is typically $\Delta\lambda\cong$50 *nm*, which is too narrow for CFs in the visible ($\Delta\lambda\cong$ 400 *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 external component transmits only one circular polarization and recycles the opposite one thus increasing the useful radiation by about 60%. We'll assume here a RH BBP which reflects RH polarization (RHP) and transmits LHP. The second layer is a pixilated 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

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reflects (and recycles) the LH Green & Blue components.

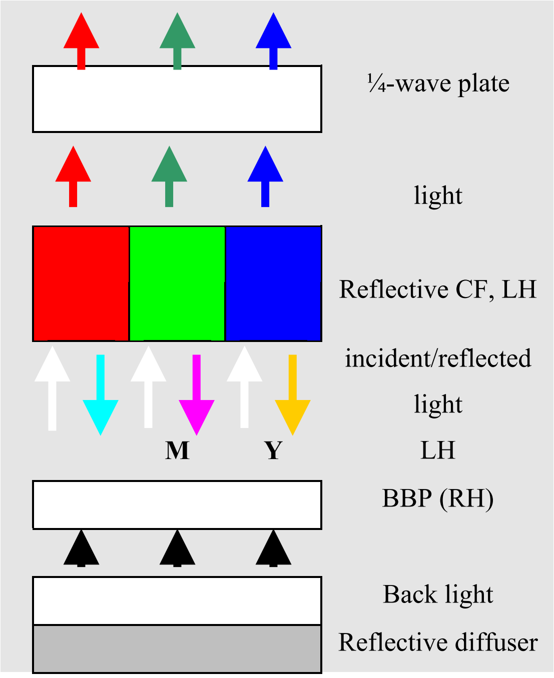

Figure 1. Structure of a reflective cholesteric CF.

The third layer is a ¼-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. A top view of a complete CF is shown in Fig. 2. Pixel size is 100 x 300 $\mu m$.

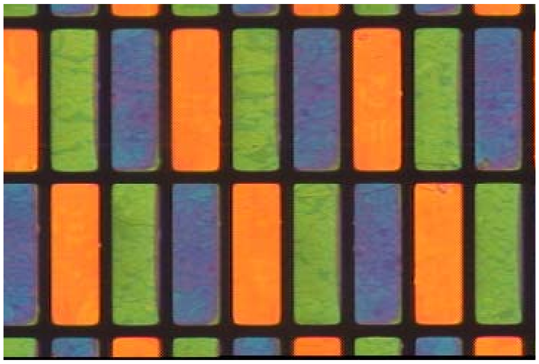

Figure 2. Front view of a cholesteric CF.

In the absence of any absorption a light recycling system should be highly efficient irrespective of the aperture ratio. Real systems, however, posses residual absorptions. Since this is a multi-pass system, the cumulative effective absorption is significantly higher than in single-pass systems. We measured transmission as high as 46% at normal incident for some of our prototypes.

## Process

A glass substrate is coated first with a BM (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 exposed 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. The ¼-waveplate is made of a thin nematic polymer coating.

## Transmission curves and colors

The above process provides a considerable flexibility 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. 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.

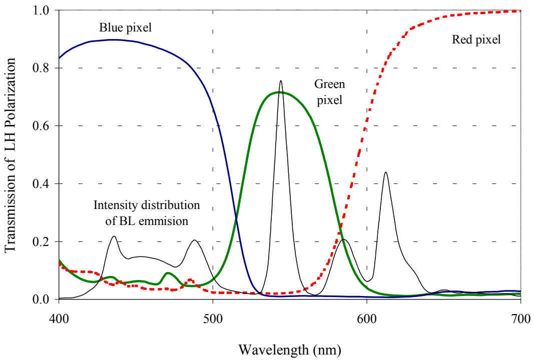

Figure 3. Typical CF transmission curves superimposed on a typical spectrum of a commercial backlight.

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

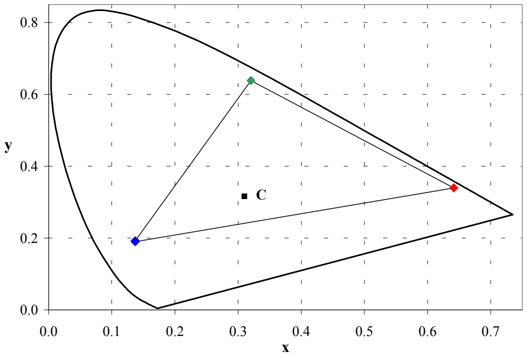

Figure 4. Color gamut in terms of *CIE* color coordinates (*x, y*)

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% |

### Contrast Ratio 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 contrast curves: CR =Tr(of LH light) / Tr(of RH light). For contrast measurements LH (RH) polarized light was achieved by using commercial circular sheet polarizers. Examples of the measured extinction curves are shown in Fig. 5.

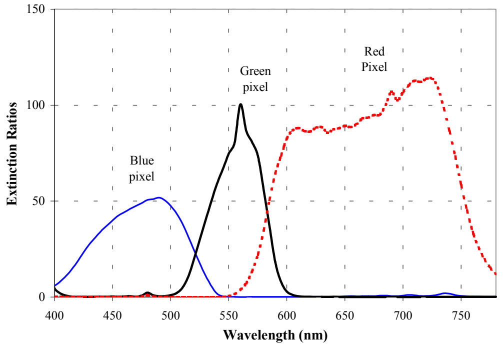

Figure 5. Extinction curves of three single color cells.

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 |

In order to integrate the reflective CFs into TN displays they were coated with ITO and were subjected to temperatures exceeding 180°C, which are required for PI coating, without major shifts in their optical properties. Currently our best photopic contrast ($CR=Y_{bright}/Y_{dark}$), measured on top of a commercial backlight and averaged over all pixels, is CR = 66 with photopic transmission of 16%. Further tuning and better process control are expected to bring the contrast in line with industry standards.

### Brightness enhancement

In order to estimate the brightness gain due to light recycling by the BBP we measured the luminance from a **BL | BBP**(RH) system without a CF. The backlight consisted of a commercial light guide with 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 photopic transmission was T=46±4%. We compared the luminance of our prototypes (aperture ratio = 73%) to a conventional absorptive color filter in a standard configuration: **BL | Linear Polarizer | Absorptive CF** (aperture ratio = 38%). For conventional CF we measured a photopic transmission of T=5.8%. From this comparison we estimate that the average total brightness enhancement for our patterned cholesteric CFs is: 8.1 or 4.2 when adjusted to equal apertures.

### 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.