Advancements in 3-D Stereoscopic Display Technologies: Micropolarizers, Improved LC Shutters, Spectral Multiplexing, and CLC Inks

Leonard Cardillo and David Swift
VRex, Inc., Elmsford, New York

John Merritt
Interactive Technologies, Princeton, New Jersey

An overview of four new technologies for stereoscopic imaging developed by VRex, Inc., of Elmsford, New York, is presented. First, the invention of μPol micropolarizers has made possible the spatial multiplexing of left and right images in a single display, such as an LCD flat panel or photographic medium for stereoscopic viewing with cross-polarized optically passive eyewear. The μPol applications include practical, commercially available stereoscopic panels and projectors. Second, improvements in fabrication of twisted nematic (TN) liquid crystals and efficient synchronization circuits have increased the switching speed and decreased the power requirements of LC shutters that temporally demultiplex left and right images presented field-sequentially by CRT devices. Practical low-power wireless stereoscopic eyewear has resulted. Third, a new technique called spectral multiplexing generates flicker-free field-sequential stereoscopic displays at the standard NTSC video rate of 30 Hz per frame by separating the color components of images into both fields, eliminating the dark field interval that causes flicker. Fourth, new manufacturing techniques have improved cholesteric liquid crystal (CLC) inks that polarize in orthogonal states by wavelength to encode left and right images for stereoscopic printers, artwork, and other 3-D hardcopy.

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Introduction

Since Wheatstone (1838) first reported that binocular disparity is the cue for stereopsis, or what he called "seeing in solid," many new techniques and devices for producing stereoscopic views from left and right perspective flat images have evolved.[1] Beginning with the Helioth–Wheatstone stereoscope, every new technique or device has in common some advancement in one or more of the three necessary conditions to simulate depth: (1) a means to capture left and right perspective views; (2) a means to combine, or multiplex, those views; or (3) a means to deliver each view to the correct eye, or demultiplex. The Wheatstone stereoscope had (1) two perspective views captured by artists, or, early in the history of photography, captured by twin photographs; (2) as a means of multiplexing, simply placing the views side-by-side on the same stereogram viewing card; and (3) as a means of demultiplexing, providing a viewing aperture and convergence optics for each eye in front of the stereogram and a septum between the viewing apertures.

A breakthrough in stereoscopy was the invention of practical polarizers by Edwin Land[2] in 1932, with Land devising[3] the cross-polarized multiplexing/demultiplexing technique for stereoscopic films in 1935. Improvements in the 3 necessary conditions to simulate depth came from (1) the rapid development of dual motion picture cameras by Zeiss-Ikon and Ciné-Kodak; (2) multiplexing by superimposing on a metallized screen a projection of the left image through a P1 state polarizer and the right image through a P2 state polarizer; (3) demultiplexing with polarized glasses, P1 state at the left eye and P2 state at the right eye to pass polarized light of the same phase and extinguish cross-polarized light.

Land's technique has been noted because many innovations in stereoscopy, including the four to be outlined here,

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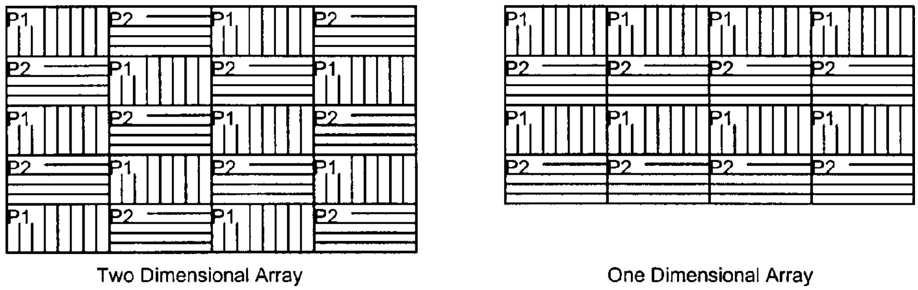

Figure 1. One- and two-dimensional μPol arrays. The one-dimensional pattern is used for TFT-LCD displays, with a half-period resolution of 201 μm used for commercially available 1280 × 1024 panels. Now μPols with half-period resolutions less than 20 μm are possible with present manufacturing techniques.

are based in some way upon cross-polarization. We will outline the following:

1. μPol micropolarizers for spatial multiplexing.
2. Improved LC shutters and electronics for temporal multiplexing.
3. Spectral multiplexing for flicker free video at standard video rates.
4. Cholesteric liquid crystal (CLC) inks.

The μPol

The μPol, invented by Faris in 1991, provided the necessary multiplexing and demultiplexing functions for stereoscopic LCD displays and stereoscopic hardcopy printing.[4] The μPol is a passive optical element that transforms incident unpolarized light into periodic, spatially varying (square wave form) polarized light with polarization alternating between two orthogonal states P1 and P2 (linear or circular). The most common fabrication method for μPol is photo-lithography to form a specific micropattern. An additive method prints a pattern on the PVA surface with a high-precision gravure cylinder and iodine-based dichroic ink, producing P1 and P2 micropolarizers; a subtractive method prints the desired pattern on the PVA with photoresist, then bleaches away exposed parts, producing a λ/2 waveplate in a pattern to be optically coupled with a polarized source.[2] When the image source is a Thin-Film-Transistor (TFT)-LCD panel, all transmitted light is polarized in a P1 state since a P1 "analyzer" is incorporated over the electrically controllable birefringent (ECB) "light valve" that turns each pixel on or off. With the patterned μPol placed over the panel, active portions of the λ/2 waveplate rotate the phase of light polarization from P1 to P2, while ablated portions leave P1 unchanged.

As illustrated in Fig. 1, the μPol can be either a one-dimensional or two-dimensional array with half-periods as small as 20 μm possible with current manufacturing processes. For TFT-LCD displays, the one-dimensional pattern is used, the finest resolution to date having a half-period of 201 μm on a 15″ diagonal 1280 × 1024 panel.

The first step in creating the stereoscopic image is by spatially multiplexing the left and right perspective views of a 3-D scene, as illustrated in Fig. 2. The left and right images, which are represented by pixel arrays, are spatially modulated with the modulators MOD and $\overline{\text{MOD}}$, producing the spatial patterns that are then combined into a spatially multiplexed image (SMI). The multiplexing algorithm can be implemented in software, hardware, or by optical means; the μPol itself can perform the multiplexing function when placed in front of the CCD array of a camera or a photographic medium.

By placing a μPol in contact with an SMI having the same spatial period, the demultiplexing step is carried out as shown in Fig. 3. The μPol codes each pixel of the right

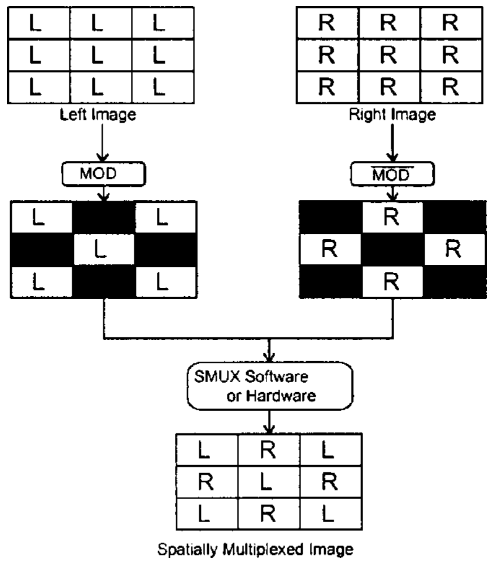

Figure 2. Spatial multiplexing. Images from digital sources are multiplexed with software, images from video sources are multiplexed with field-switching hardware, and photographic images can be multiplexed using the μPol array self-aligned to the film for both multiplexing and demultiplexing. Two-dimensional multiplexing is shown.

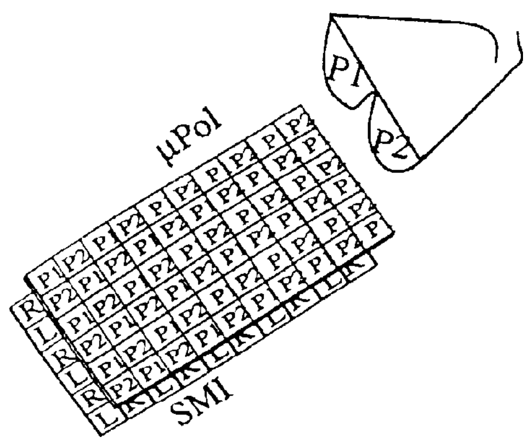

Figure 3. Demultiplexing a spatially multiplexed image (SMI). Right image pixels are aligned with the P1 elements of the μPol array, left image pixels with P2 elements. Through cross-polarization, only the right image pixels are transmitted through the polarized lenses to the right eye and left image pixels to the left eye.

image with a polarization state P1 and each pixel of the left image with state P2, thus encoding the two images. The viewer, wearing a pair of polarized glasses (or looking through a polarized visor), is able to view the right image only with the right eye and the left image only with the left eye, fusing the two views into a stereoscopic image.

Because the left and right image information is simultaneously present in a single frame, the technique is general purpose. The SMI could be displayed by conventional devices, printed by conventional printers, recorded by photographic cameras, and video cameras, or projected by a single slide or a single movie projector. In all cases, color 3-D stereo images can be produced. In contrast, techniques that produce stereo images by means of two separate left and right frames (sequential or in parallel) do not have the μPol's range of application and are also incapable of producing 3-D hardcopy.

μPol Applications and Products. VRex has incorporated μPol technology in commercially available 3-D stereoscopic LCD panels and projectors ranging from 640 × 480 pixel resolution to 1280 × 1024. Other μPol-based devices in production include a 3-D LCD notebook computer, an interactive 3-D information center utilizing a touch-screen LCD and polarized visor, and an immersive environment consisting of wrap-around rear-screen 3-D projection. Hardcopy has been produced using photographic medium with a self-aligned μPol for both multiplexing during exposure and demultiplexing during viewing.

Improved Liquid Crystal Shutters

A drawback to μPol display applications is their unsuitability for CRT devices. The thickness of a CRT display would position a μPol 10 to 20 mm in front of the image plane scanned on the phosphor screen, introducing parallax between horizontal image raster lines and horizontal μPol lines when viewed above or below the plane orthogonal to the CRT screen. This parallax results in a limited viewing zone, with cross-talk or pseudoscopic images perceived outside this zone. A solution lies in finding polarized material that can be coated inside the CRT in front of the phosphor screen and can withstand the intense heat generated by the cathode heater filament; until then, shutter devices are the preferred technique to demultiplex stereoscopic left and right perspective images time-multiplexed on the CRT.

The theory of operation for stereoscopic viewing of CRTs through shuttered eyewear is simple. Images are time-multiplexed so a left perspective image is displayed on the CRT device when the left eye shutter is open and a right perspective image displayed when the right eye shutter is open. At suitable repetition rates, the viewer perceives a continuously present 3-D image. In video applications, the two interleaved fields in each frame of an NTSC display provide a convenient multiplexing method: the right image encoded in Field 1, the left 16 ms later in Field 2. PC monitors driven in page-flipped or interlaced mode provide even faster repetition rates.

Early time-multiplexed implementations used mechanical shutters,[6,7] but these shutters were cumbersome and obtrusive. PLZT ceramics were an interim solution for shutters,[8] but now most devices use variations of liquid crystal (LC) shutters.[9] In general, an LC shutter consists of an electrically controllable birefringent (ECB) plate in which molecules are in a liquid-crystalline state. When an electric field is applied across the plate, the molecules align in parallel, producing a 90° phase shift between the horizontal and vertical components of linearly polarized light passing through the plate; when the field is removed, the molecules return to random alignment, passing the components of the polarized light in phase. Using a second polarizer, or analyzer, on the exit side of the plate, light is passed when a voltage is applied and the ECB plate is phase shifted, and light is extinguished when the voltage is removed and the plate is in ordinary phase. The reader is referred to Bos[10] for an excellent review of LC shutter material and operation.

Two basic liquid crystal types are the Π-cell and the twisted nematic (TN) cell; to date, most shutter glass systems have used Π-cells.[11] Although the Π phase shifting material used in these cells allows extremely fast switching times (<3 ms), they require very high excitation voltages, 20 Vp-p minimum, which makes wireless battery-powered operation difficult and costly to achieve. A second characteristic of Π-cells is that the cell is not transparent when the excitation voltage is removed; with no power applied the cell will retain a semi-opaque color hue. A low-level excitation voltage, 8 Vp-p approximately, needs to be applied to the cell to achieve transition from the full transparent to the full opaque state.

A practical time-multiplexed stereoscopic shutter system using TN liquid crystals has recently been developed.[12] A major advantage of TN cells is that, unlike Π-cells, no background excitation voltage is needed to keep the shutters in the transmissive state. However, TN cells have had the disadvantage of slow transition time (>10 ms) from the transmissive to the opaque state and back to transmissive as excitation voltage is applied and disconnected.[13] In addition, the transmissive to opaque (turn on) time may differ from the opaque to transmissive (turn off) time. However, the performance of the TN cell has been optimized both in the manufacturing process of the cell itself and in the timing of the applied excitation voltage to overcome these limitations.

A major improvement was reducing cell thickness to a minimum for faster switching and lower excitation voltages. This was key to obtaining long battery life in wireless battery shutter glasses because no high-voltage dc–dc converters would be required as with Π-cell shutters. During normal operation, the shutter drivers draw 130 μA when shutters are transmissive with a DC signal, 150 μA with a 60-Hz signal and 200 μA with a 120-Hz signal. Each shutter can switch at frequencies in excess of 120 Hz with no interfield cross talk. Higher frequency switching was accomplished by synchronizing shutter transitions with video fields. Previous devices synchronized the shutter transition to the beginning of each video field: once a vertical reset pulse or similar signal was detected, pulse coded information was sent to toggle the optical state of the shutters. For the shutters to change state before the first line of displayed video, the pulse codes had to be very short, requiring high speed circuitry in the receiver that consumed much power. To reduce the power requirements of the present system further, the field identification information is sent *prior* to the vertical blanking interval so the pulse information may be transmitted at a much slower rate. The detection circuitry functions at a slower frequency and battery life is greatly increased.

A further improvement implemented in the stereoscopic shutter system was the ability to synchronize the shutters to all popular display formats used by TVs and PCs: the IR transmitter that sends driving codes to the shutters in the eyewear can detect synchronization signals, polarities, and frequencies present in all VGA, SVGA, and XGA computer formats, as well as NTSC and PAL video sources. The image field rate and the mode of operation, i.e., 2-D, 3-D interlaced, or 3-D page flipped, is determined

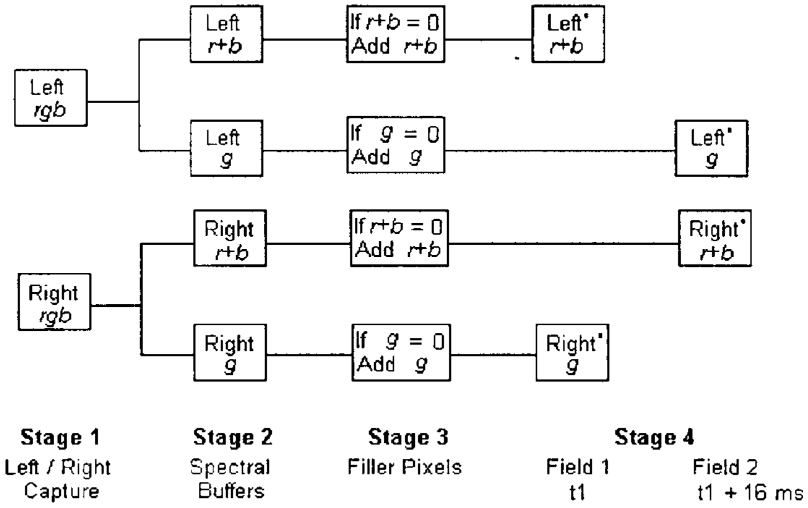

Figure 4. Stages of spectral multiplexing. In Stage 1, *r,g,b* image pixels are captured and in Stage 2, pixels are separated into a magenta buffer ($r + b$) and a green buffer (g) for the left and right images. In Stage 3, filler pixels are added so pure red, green, blue, or magenta areas of the image will not be dark during the alternate field. Stage 4 shows the field-sequential presentation of left and right images.

from these signals. Detecting carrier synchronization signals is a benefit because earlier attempts at field coding required tagging the video content itself with black and white markers on a horizontal scan line.[14]

Shutter Applications and Products. The largest commercial application of the improved LC shutters is in stereoscopic eyewear called VR Surfer. System software enables the user to optimize the performance of the shutter system to a particular PC monitor: a basic mode of operation is provided that encodes image identification information in the display sync signals during the vertical reset interval. This mode will enable the display of stereoscopic images in DOS applications but does possess some degree of perceived image flicker because the image switching rate is in the 60 to 72-Hz range. An advanced mode detects the video card chip set driving the PC monitor and will automatically implement the best stereoscopic display mode at rates up to 120 Hz. In this mode, Microsoft Windows applications are supported. The system is also compatible with field-sequential stereoscopic video in NTSC and PAL standards.

While the improved LC shutters have been used chiefly for demultiplexing in eyewear, a device is under development that uses the shutters to multiplex stereoscopic perspective views to a single CCD recording device. Specifically, if a beam splitter is placed in the primary viewing path of a video camera and mirrors relay a second perspective view offset from the primary, the left and right perspectives necessary for a stereoscopic view will be imaged on the CCD. By placing a pair of LC optical shutters in each of the viewing paths, each viewing perspective can be alternately imaged by the camera if the shutters are opened and closed in synchronization with the video field output. By convention, the right perspective will be encoded in Field 1 of the video frame and the left perspective in Field 2. A promising commercial application for the device is as an attachment for the home video camcorder.

Spectral Multiplexing

Because of the predominance of television as a display medium, it would be beneficial if field-sequential multiplexing could operate at NTSC television standard 60-Hz field rates with no flicker at all. In the 60-Hz standard field-sequential LC shutter system just described, some residual flicker is perceived because left and right images are coded in one field of video so there is alternately in each eye the full brightness of the image and a 16.6-ms dark interval. The human visual system will integrate light energy over time, reaching a critical fusion frequency (CFF) beyond which these alternating light and dark intervals are perceived as steady, but at normal viewing luminance, the 60 Hz field rate is[15,16] below the CFF. Flicker is more apparent with brighter displays, the fusion threshold increasing with the logarithm of luminance according to the Ferry–Porter law,[17] and the contours defining images increase the threshold even more because contrast increases with fast visual "off" transients generated at image offset.[18] While some evidence exists that visual persistence of stereoscopic stimuli is longer than mono-planar stimuli,[19,20] thus decreasing the fusion threshold, the effect is not long-lasting enough to bridge the 16-ms dark interval. To prevent flicker, a new field-sequential system is under development that eliminates the dark interval within the video frame, maintaining light energy at both eyes at all times, decreasing or eliminating luminance modulation between video fields.[21]

Figure 4 shows the image capture and multiplexing functions of the spectral multiplexing technique.

In Stage 1, left and right perspective views from cameras or computer graphics are captured and analyzed on a pixel-by-pixel basis. In Stage 2, each is separated into two spectral buffers: one for red and blue ($r + b$) and one for green (g). (Note that "pixel" here refers to an individual color component, not one of three points comprising a color.) The luminance at each eye is of different wavelength components, but these will still summate luminance to decrease the CFF relative to light/dark stimulation.[22] At this stage, the pixel data in the buffers could be field-sequentially multiplexed, as shown in the final stage, so each eye receives light energy during both Field 1 and Field 2 presentations, a technique similar to that described by Street.[23] However, pixels that represent a pure primary color (r or b or g) or magenta ($r + b$) will not have spectral components in one of the buffers and will still be dark

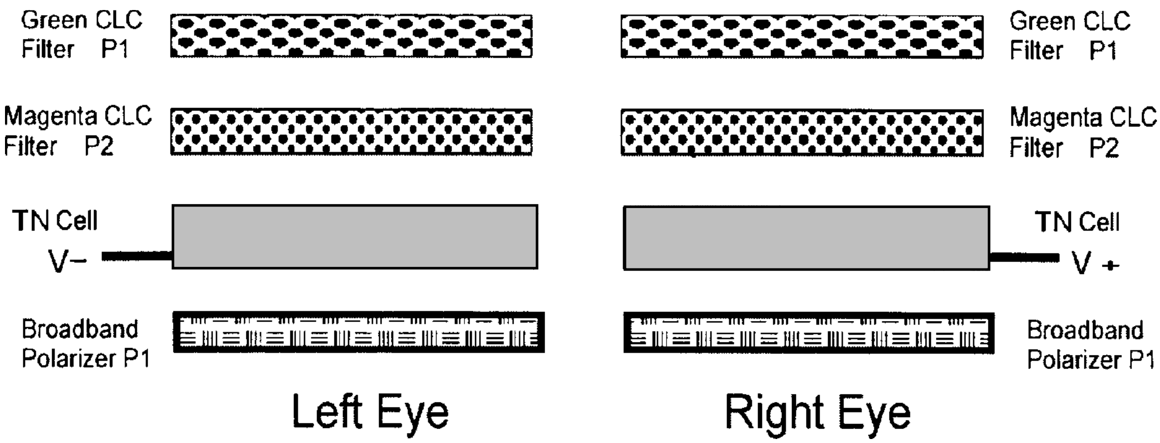

Figure 5. Eyewear for spectral demultiplexing. Left and right eye optics are identical: shown in order from the image back to the eye are green cholesteric liquid crystal filters in a P1 state, magenta cholesteric liquid crystal filters in a P2 state, active TN cells, and a broadband polarizer (analyzer) in a P1 state. The TN cells are shown in a state to transmit the Field 1 image; to transmit the Field 2 image, the voltage polarities are reversed.

during one field. The advancement over Street's technique is in maintaining some spectral luminance at the eye even when a primary- or magenta-colored object has no spectral components in the subsequent field. Therefore, at Stage 3 each pixel is analyzed, zero values identified, and a "filler pixel" inserted. A pixel of a suitable minimum luminance value replaces dark $r + b$ pixels in one buffer or g pixels in the other buffer for each eye's view, maintaining energy at all pixels in both eyes during both Field 1 and Field 2. The luminance of filler pixels from the alternate buffer is chosen to shift the chromaticity or saturation of the r,g,b, or magenta color a minimum perceived amount in color space[24] yet maintain enough energy during the otherwise dark field to prevent flicker. This is possible because the visual system does not discriminate colors perfectly, with observers perceiving similar colors with substantial shifts in wavelength. Attempted isomeric or metameric matches to a given wavelength show large just noticeable differences (JND) in chromaticity space as well as saturation space.[25] Suitably chosen color pixels can be added to the otherwise dark pixel space in the alternate field to summate with the luminance of the primary r,g,b or magenta pixels, resulting in minimum shifts in perceived color yet decreasing luminance modulation, so flicker is not perceived.

After the frame buffers are updated with "filler pixel" data, the buffers are shifted into the NTSC field format in Stage 4: $r + b$ pixels from the left view and g pixels from the right view into Field 1; g pixels from the left view and $r + b$ pixels from the right view into Field 2. An ordinary CRT monitor with NTSC video input displays the field sequential information directly or from standard recorded video tape.

Figure 5 shows the implementation of the spectral demultiplexing function at the eyes, with eyewear consisting of passive green and magenta CLC filters, active electronic TN cells, and passive broadband polarizers.

The CLC filters pass their respective colors circularly polarized, right-hand polarized greens (P1) and left-hand polarized magentas (P2). The TN cells are EBC devices synchronized with Field 1 and Field 2 of the NTSC signal using the same circuit techniques described previously. During Field 1, the left eye's TN cell is activated (V-), reversing the polarized state passed by the filters while the right eye's TN cell is inactive (V+), maintaining the polarization. Figure 6 shows the Field 1 state of the TN cells; during Field 2 the right eye's TN cell switches to V- and the left to V+. The broadband polarizer, or analyzer, passes P1 light and blocks P2.

Referring to Fig. 4, Stage 4, the CRT monitor displays $r + b$ (magenta) information from the left eye image and g information from the right eye image simultaneously during Field 1. During Field 2, g information from the left eye and $r + b$ information from the right eye is displayed simultaneously. By alternately activating and de-activating the TN cells in synchrony with Field 1 and 2, it can be seen that the eyewear performs the appropriate spectral demultiplexing function, passing left and right image information to the correct eyes for field-sequential stereopsis without flicker.

3-D Printing Based on CLC Inks

A new method of printing 3-D images has been made possible through several patented processes for manufacturing inks based on CLC materials.[26,27] This CLC ink can be made right circularly polarized (RCP) as well as left circularly polarized (LCP) to enable polarization multiplexing of the left and right images, with circularly polarized 3-D glasses demultiplexing images. Applications for these new inks include 3-D hardcopy from inkjet printing, offset printing, gravure, and silk-screen processes that can be printed on any paper, fabric, or other medium.

CLC Properties. CLC is a nematic liquid crystal with chiral additives or polysiloxane side-chain polymers that cause the cigar-shaped molecules to be spontaneously aligned in an optically active structure both LCP and RCP. Chiral additives give the CLC molecules a degree of twist and helical structure with pitch "p." (Pitch can be thought of as the length of a bolt that a nut must travel to make a 360° turn, tighter pitch resulting in less travel.) The higher the concentration of the chiral additive, the tighter the molecules are arranged in the helix, resulting a shorter pitch. CLCs can be either left-handed (LH) or right-handed (RH), each having a unique property known as selective wavelength reflection. When light is incident upon the CLC surface, the selective reflection is described by the following equation:

$$\lambda = \lambda_o = n_a\, p, \tag{1}$$

where λ is the reflective wavelength, n_a is the mean index of refraction (approx. 1.6) of the CLC material, and p is

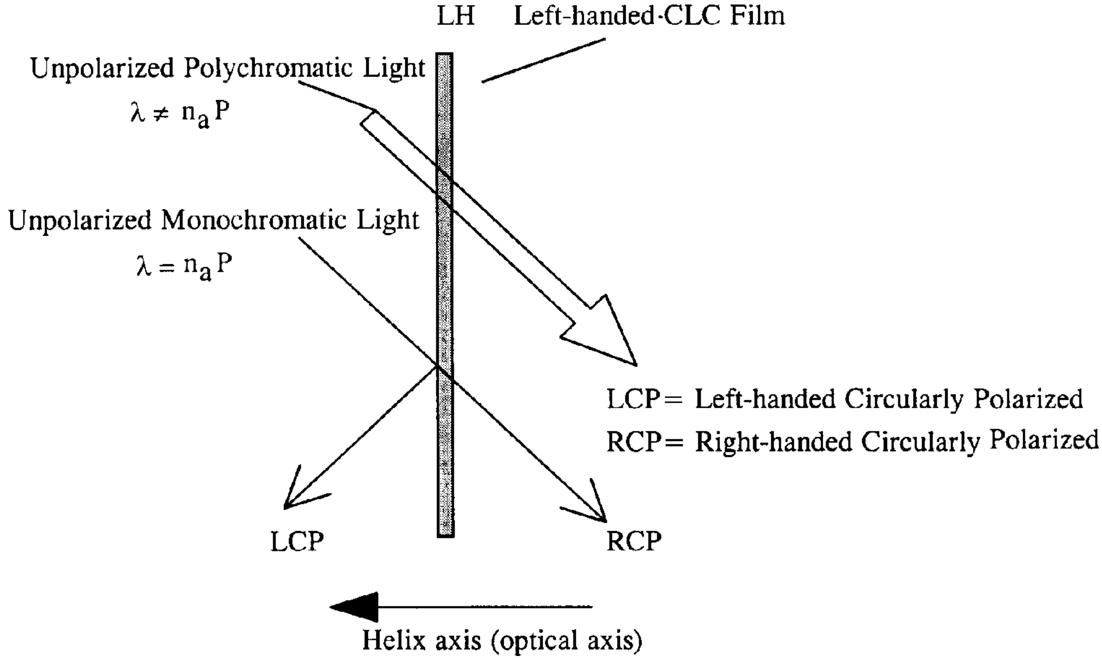

Figure 6. Reflective properties of left-handed CLC. The wavelength of light reflected is determined by the pitch of the CLC, and the direction of polarization, RCP or LCP, is determined by the direction of helical twist of the CLC.

the pitch of the helical structure. Figure 6 illustrates the selective reflection of LH CLCs.

If the CLC is RH, then it reflects 50% of the incoming light at the selected wavelength in RCP light and transmits 50% of that wavelength in LCP light. All other wavelengths are transmitted through the material. Similarly, LH CLC material will reflect LCP light and transmit RCP light. The reflected wavelength, or color, can be tuned by changing the length of the pitch, which is dependent on the chiral additive concentration. The polarization of the reflected light, RCP or LCP, can be altered by using RH or LH CLC material.

New CLC Ink Fabrication Processes. A major breakthrough in CLC ink fabrication was a process to make the inks useable at room temperature. Formerly, room-temperature use required CLC to be in the liquid phase, encapsulated or confined to cells; in the solid phase, the CLC inks had to be applied at very high temperature. In the new process,[26] molten CLC material above the glass temperature (for polysiloxane-based CLC polymers, about 120°C to 150°C) is deposited onto a rotating belt and aligned using a knife edge. After a cooling stage, the CLC film is transferred to another rotating belt coated with an adhesive. The second belt, after receiving the CLC film, goes through an air jet stage where an ultrasonic air jet or air jet with fine powder abrasives removes the ultrabrittle CLC film from the adhesive. The result is tiny CLC flakes that retain the helical structure normal to the CLC flake surface. The CLC flakes range in thickness from 1 to 20 μm and in size from 5 to 75 μm with an average size of 25 μm. The geometry of the flakes can be regular or irregular.

To produce the CLC inks, these CLC flakes are mixed with a host fluid or host matrix, the carrier. The carrier must be chosen for suitable tackiness, drying speed, adhesion to surfaces, friendliness to environment, etc., depending on the application: offset printing, ink-jet printing, painting, drawing, xerography, or other imaging methods. When the CLC flakes are mixed with a suitable host matrix such as wax or other sticky material that is a solid at room temperature, crayons, pencils, or other drawing devices can be made.

Printing 3-D Images using CLC Inks. Unlike conventional pigments and dyes, CLCs work on a reflective mechanism, with six types of crystal necessary to render the visible spectrum in two polarization states: red, blue, and green pitched crystals in LCP and RCP states. (In practice, it has been found necessary to use two additional types, namely, white pitched crystals in each polarization state). Instead of printing or plotting on a white piece of paper, CLCs are applied onto light absorbing or nonreflective surfaces. When viewed by itself, the ink appears almost transparent. When the ink is applied to a black paper or other medium, the color corresponding to the wavelength of the CLC material can be seen. All of the other colors are absorbed by the black medium. Moreover, if viewed with an RCP or LCP polarizer, the CLC material will be seen only through the same-phase polarizer. It is the circular polarization property of the CLC inks that is used to multiplex left and right images for 3-D stereoscopic printing, the left image put on the black substrate using LCP ink and the right image using RCP ink. The 3-D images are demultiplexed at the eyes by cross-polarization through ordinary circularly polarized glasses.

Conclusion

Four new advancements in 3-D stereoscopic display technology developed by VRex, Inc., of Elmsford, New York, have been outlined. µPol optics have been applied to 3-D LCD displays with benefits of reduced cost, self-alignment of images, compatibility with video and computer standards, and single projector implementation of 3-D, leading to commercial desirability over other cross-polarization displays for multiple viewers. Improvements in LC shutter materials and electronics have led to commercially desirable 3-D eyewear for personal viewing of stereoscopic 3-D images from TVs and PCs, while the technique of spectral multiplexing, now under development, promises flicker-free time-multiplexed stereoscopic content from popular, low-cost 60-Hz TV and video displays. Finally, advancements in CLC inks have led to stereoscopic hardcopy printable on any medium. The first practical CLC applications are for posters and clothing using a silk screen process, with other printing techniques, including ink jet, under development.

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