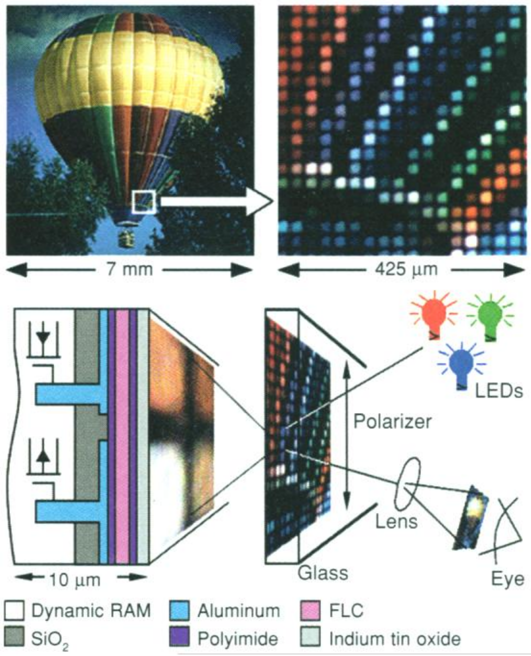
Fast Ferroelectric Liquid-Crystal Electrooptics

David M. Walba

Many emerging technologies, including remote learning and video teleconferencing, interactive television, desktop digital audio-video, and the World Wide Web, share a common problem: a need for ever higher data transfer rates. Owing to power dissipation limits of conventional electronics, it seems likely that optical encoding of data will be an important part of the solution. Nevertheless, the silicon chip will be here for a long time to come. Silicon by itself, however, is a poor choice for modulation of light with electronics. These facts of digital life are currently driving an exciting research area aimed at development of electrooptic (EO) materials capable of working with silicon to create a class of devices sometimes termed integrated optical chips (*1*).

Organic thin films are among the most promising such materials. Design and synthesis of organic optical chips involve three key tasks: (i) Molecules enabling the required EO performance must be created; (ii) the molecules must be assembled into a material with the correct supermolecular stereochemistry to afford the required optical quality and EO properties; and (iii) this material must be properly integrated with a semiconductor device—a key process requiring supermolecular organization on a more global level.

The grandparent of organic EO films is the nematic liquid crystal (LC). Nematic LC molecules are highly anisotropic with respect to interaction with electric fields at low frequencies and with optical fields, properties useful for EO modulation. Self-assembly provides an elegant solution to the problem of supermolecular organization (the second task for realizing organic integrated optics), and the excellent processibility of LCs provides an approach for accomplishing that crucial third task of integration on silicon. This powerful combination has enabled the production of first-generation optical chips: LCs on amorphous-silicon integrated chips, which have been incorporated into video-camera color viewfinders as well as some of the first consumer virtual reality headsets. In this application, the EO modulator converts digital electronic data into optical signals in a large number of channels running in parallel. Here the optical signals are not destined for another chip, but rather are beamed into the human brain through that most highly evolved EO receiver—the eye.



Prototype spatial light modulator. The 7 mm × 7 mm active area of the device is shown at upper left. The photomicrographs (of the same chip being driven by a computer) were taken with time-sequential illumination from red, green, and blue light-emitting diodes (LEDs) using a shutter speed of 1/60th second. [Photomicrographs courtesy Displaytech, Inc.]

For many applications, however, nematic LC modulators are either too slow, too large, or both. Enter chiral smectic-C ferroelectric LCs (FLCs) (*2*). FLCs are a unique state of matter: true liquids with a polar supermolecular structure (*3*). Thus, FLCs combine the processibility of LCs with many valuable properties of well-known inorganic polar-effect materials, such as lithium niobate and potassium titanyl phosphate, including many types of EO effects that do not occur in the nonpolar nematic LCs.

For example, the polar structure of the FLC self-assembly leads to a macroscopic electric dipole moment termed the ferroelectric polarization. Although the magnitude of this macroscopic dipole is typically relatively small on a per molecule basis (~0.01 D per molecule, although values as high as 3 D per molecule have been observed)—because the ferroelectric polarization scales with the number of molecules in the sample—in a film 1 μm by 1 cm^2, the macroscopic dipole moment is on the order of 10^{15} D. Even a single ferroelectric domain on the order of 1 μm by 5 μm by 5 μm in size has a dipole moment on the order of 10^8 D. It is therefore not surprising that FLC films respond more strongly to applied electric fields than conventional LCs. In the surface stabilized (SS) FLC device invented by Clark and Lagerwall (*4*), EO switching in thin films is fast, of very high contrast, and intrinsically digital (that is, the switches are either on or off, depending on the sign of the applied field, with a sharp switching threshold and bistable memory).

The size scale, speed, and power dissipation characteristics of SSFLC switches are well fitted to the ubiquitous VLSI (very large scale integration) silicon (*5*), leading to a new type of integrated optical chips (see figure) (*6*). These devices, referred to as spatial light modulators (SLMs), are essentially write-only silicon memory chips with optical read-out. With 256 × 256 = 64K channels running at 10 kHz, the prototype VLSI-FLC SLM pictured in the figure can convert electronic data to optical form at about 0.5 Gbit/s. One application of such devices is in projection or personal information display. The data rate of the SLM is directly visible in the figure: All of the perceived color and gray scale information seen in the photomicrographs results from time-averaging of one-bit digital frames; the high data rate enables display of 15-bit full-color images at 60 frames per second. Next-generation devices with 1280 × 1024 channels running at 10 kHz will drive 10 Gbits/s.

This is achieved by running many channels in parallel at a slow rate per channel. For information display and many other applications, this approach is ideal. For some applications, such as sending data along high-speed networks, a single channel running at 10 Gbits/s or faster is required. This kind of speed is impossible with standard LC switching, even for FLCs, because the EO effect derives from large motions of the molecules, which cannot occur at rates much faster than 1 MHz with the small driving fields available from standard VLSI silicon. Ultrafast EO modulation can be obtained, however, by taking advantage of another property of organic materials: electronic second-order nonlinear optics (NLO).

Thus, organic materials can exhibit an ultrafast EO effect caused not by motions of

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The author is in the Department of Chemistry and Biochemistry and the Optoelectronic Computing Systems Center, University of Colorado, Campus Box 215, Boulder, CO 80309-0215, USA, and is a cofounder and member of the board of Displaytech, Inc., 2200 Central Avenue, Boulder, CO 80303, USA. E-mail: walba@colorado,edu

molecules or atoms but rather by motions of electrons. This effect is much weaker than LC molecular switching and typically requires much larger devices for the same degree of interaction with light at a given modulating field strength, but it can deliver blistering speed, an acceptable tradeoff for ultrafast single-channel modulators. In order to achieve useful NLO-based switching, however, supermolecular stereocontrol is again required, one in which very specific arrays of functional groups are oriented correctly in space. Because such materials are typically colored, these functional arrays are often termed NLO chromophores.

The most straightforward approach to organic NLO materials involves orientation of NLO chromophores along the polar axis of a sample with macroscopic polar symmetry. A very intensively studied approach for achieving this structure involves application of an external electric field to an organic polymer film containing NLO dye molecules with large dipole moments, using an external electric field, then freezing in the resulting polar structure by lowering the temperature of the sample to below the polymer glass transition. Great success in obtaining films with useful EO properties has been achieved in this way, and ultrafast optical circuits using such poled polymers are being demonstrated. However, problems remain, and several alternative approaches are under investigation.

Because FLCs spontaneously self-assemble into a polar structure, and techniques for processing FLC films on VLSI silicon are already relatively highly developed, FLC materials with useful NLO properties would complement poled polymers, providing increased flexibility in design and fabrication of NLO switches. Early NLO experiments with FLCs, however, showed that typical materials used in displays have NLO figures of merit on the order of 10^5 too small. Some understanding of the molecular origins of the polar structure occurring in FLCs has allowed the design of materials improved by about 10^4 in EO properties (*7*); however, at least an additional order of magnitude improvement is required in order to create useful ultrafast FLC NLO chips.

Until recently, this goal seemed elusive because of a very fundamental LC principle: LC molecules possess a large steric aspect ratio (that is, the molecules are long and skinny). Furthermore, in the FLC phase the long axis of the molecules is perpendicular to the polar axis of the material. Because most NLO chromophores are long functional arrays, they tend to orient perpendicular to the FLC polar axis as well, leading to incorrect supermolecular stereochemistry and poor NLO properties.

This problem now appears tractable, given the recent synthesis and characterization in our laboratories of FLC side-by-side dimer structures wherein the chromophore of the prototype NLO dye disperse red 1 (DR1) orients along the polar axis (normal to the LC long axis) in the FLC phase (*10*). The materials possess excellent liquid crystallinity; polarized light spectroscopy, ferroelectric polarization measurements, and powder x-ray scattering combine to show that the materials self-assemble to give the proper supermolecular stereochemistry for NLO. Thus, it seems reasonable to hope that FLCs with NLO properties on a par with poled polymers will be achievable, paving the way for the creation of ultrafast VLSI-FLC EO modulators similar in basic structure to the device shown in the figure.

Several key issues need addressing before realization of this goal, however. These issues revolve around the fact that it will likely be necessary for the light to propagate parallel to the plane of the FLC film in NLO-based devices, requiring guided wave optics. Very little work on FLC wave guiding has been accomplished to date, and key aspects of the problem such as temperature sensitivity and optical clarity have not yet been addressed. However, it is clear that because their unique supermolecular structure, FLCs offer a highly attractive potential approach to both highly parallel and ultrafast transmission of information with light.

References and Notes

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A Heterodimeric Transcriptional Repressor Becomes Crystal Clear

Brenda J. Andrews and Michael S. Donoviel

Over the past decade or so, studies of cell-type determination in budding yeast have consistently affirmed the predictive power of genetics—complex hypotheses, based solely on the analysis of mutants, have largely withstood the scrutiny of biochemists and molecular biologists. Now, the crystal structure of a1/α2 repressor, solved by Li *et al.* and described in this issue (*1*), provides a decisive molecular view of interactions suggested by genetic functional studies in vivo. In addition, the structure provides a first glimpse at what is likely to be a common mechanism by which the activity of transcriptional regulatory proteins is altered by interaction with different partners.

Saccharomyces cerevisiae exists as three cell types with distinct physiological properties and specialized roles during the yeast life cycle (*2*). Haploid cell type is determined by a single genetic locus, *MAT*, which encodes master regulatory proteins that dictate the expression of sets of cell type–specific genes. Haploid **a** cells carry the *MAT***a** allele and express a set of **a**-specific genes. In the other haploid cell type, α, which carries the *MAT*α allele, **a**-specific genes are turned off while another set of genes (α-specific genes) is turned on. Haploid **a** and α cells can mate to form the third specialized cell type, the **a**/α diploid cell.

Transcriptional repression is crucial in controlling the expression of cell type–specific gene sets (*3*, *4*). First, in both α and **a**/α cells, the MAT α2 gene product α2 collaborates with the ubiquitous transcription factor Mcm1 to form a heterodimeric repressor which binds to the **a**-specific gene operator that lies upstream of **a**-specific genes. As a result of α2-Mcm1 binding, **a**-specific genes are turned off (*5*, *6*). Second, in **a**/α diploid cells, α2 performs another function; it binds cooperatively with the *MAT***a** gene product **a**1 to the haploid-specific gene operator to turn off haploid-specific genes (*6*, *7*). The **a**1 and α2 proteins are related: They belong to the homeodomain family of proteins that regulate transcription in a wide range of eukaryotic organisms (*8*). Like some other homeodomain

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The authors are in the Department of Molecular and Medical Genetics, University of Toronto, Toronto M5S 1A8, Canada.