

AFRL-ML-WP-TP-2006-473

**SELF-ACTIVATED LIQUID CRYSTAL
CELLS USING PHOTOVOLTAIC
SUBSTRATES (POSTPRINT)**

Jennifer L. Carns, Gary Cook, Mohammad A. Saleh,
Svetlana V. Serak, Nelson V. Tabiryan, and Dean R. Evans



JANUARY 2006

Approved for public release; distribution is unlimited.

STINFO COPY

© 2006 Optical Society of America.

The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work.

**MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750**

NOTICE AND SIGNATURE PAGE

Using Government drawings, specifications, or other data included in this document for any purpose other than Government procurement does not in any way obligate the U.S. Government. The fact that the Government formulated or supplied the drawings, specifications, or other data does not license the holder or any other person or corporation; or convey any rights or permission to manufacture, use, or sell any patented invention that may relate to them.

This report was cleared for public release by the Air Force Research Laboratory Wright Site (AFRL/WS) Public Affairs Office and is available to the general public, including foreign nationals. Copies may be obtained from the Defense Technical Information Center (DTIC) (<http://www.dtic.mil>).

AFRL-ML-WP-TP-2006-473 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

*//Signature//

DEAN R. EVANS, Physicist
Exploratory Development
Hardened Materials Branch

//Signature//

TIMOTHY J. BUNNING, Acting Chief
Hardened Materials Branch
Survivability and Sensor Materials Division

//Signature//

DANIEL J. BREWER, Acting Chief
Survivability and Sensor Materials Division

This report is published in the interest of scientific and technical information exchange, and its publication does not constitute the Government's approval or disapproval of its ideas or findings.

*Disseminated copies will show “//Signature//” stamped or typed above the signature blocks.

REPORT DOCUMENTATION PAGE					<i>Form Approved</i> OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE (DD-MM-YY) January 2006		2. REPORT TYPE Journal Article Postprint		3. DATES COVERED (From - To) 10/01/2002 – 12/01/2005		
4. TITLE AND SUBTITLE SELF-ACTIVATED LIQUID CRYSTAL CELLS USING PHOTOVOLTAIC SUBSTRATES (POSTPRINT)					5a. CONTRACT NUMBER In-house	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER 62102F	
6. AUTHOR(S) Jennifer L. Carns (Anteon Corporation) Gary Cook (Universal Technology Corporation) Mohammad A. Saleh (UES, Inc.) Svetlana V. Serak and Nelson V. Tabiryan (BEAM Engineering for Advanced Measurements Co.) Dean R. Evans (AFRL/MLPJ)					5d. PROJECT NUMBER M08R	
					5e. TASK NUMBER 10	
					5f. WORK UNIT NUMBER 00	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Anteon Corporation 5100 Springfield Pike, Suite 509 Dayton, OH 45431 ----- Universal Technology Corporation 1270 N. Fairfield Road Dayton, OH 45432 ----- UES, Inc. 4401 Dayton-Xenia Road Dayton, OH 45432					8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-ML-WP-TP-2006-473	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Materials and Manufacturing Directorate Air Force Research Laboratory Air Force Materiel Command Wright-Patterson AFB, OH 45433-7750					10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL-ML-WP	
					11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-ML-WP-TP-2006-473	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.						
13. SUPPLEMENTARY NOTES © 2006 Optical Society of America. The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work. Paper published in the <i>Optics Letters</i> , Vol. 31, No. 7, April 1, 2006, published by the Optical Society of America. PAO Case Number: AFRL/WS 06-0316, 7 Feb 2006.						
14. ABSTRACT We show that photovoltaic fields are capable of efficiently reorienting liquid crystals, leading to new concepts of optically addressable light modulators. Using an arrangement consisting of a liquid-crystal layer between LiNbO ₃ :Fe photovoltaic substrates, we observed spatial filtering due to self-phase modulation in a planaroriented cell and nonlinear transmission between crossed polarizers in a twist-oriented cell. These processes do not require an external electric field. The substrates are arranged such that light propagates along the +c axis in each substrate, allowing a secondary process of power transfer to occur through contradirectional photorefractive two-beam coupling.						
15. SUBJECT TERMS liquid crystal (LC), two-beam coupling, polarizer, photovoltaic						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT: SAR	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON (Monitor) Dean R. Evans 19b. TELEPHONE NUMBER (Include Area Code) N/A	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified				

Self-activated liquid-crystal cells with photovoltaic substrates

Jennifer L. Carns

Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, Ohio 45433, and Anteon Corporation, 5100 Springfield Pike, Suite 509, Dayton, Ohio 45431

Gary Cook

Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, Ohio 45433, and Universal Technology Corporation, 1270 North Fairfield Road, Dayton, Ohio 45432

Mohammad A. Saleh

Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, Ohio 45433, and UES, Inc., 4401 Dayton-Xenia Road, Dayton, Ohio 45432

Svetlana V. Serak and Nelson V. Tabiryan

BEAM Engineering for Advanced Measurements Co., 809 South Orlando Avenue, Suite I, Winter Park, Florida 32789

Dean R. Evans*

Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, Ohio 45433

Received November 22, 2005; revised December 22, 2005; accepted December 27, 2005; posted January 17, 2006 (Doc. ID 66190)

We show that photovoltaic fields are capable of efficiently reorienting liquid crystals, leading to new concepts of optically addressable light modulators. Using an arrangement consisting of a liquid-crystal layer between $\text{LiNbO}_3\text{:Fe}$ photovoltaic substrates, we observed spatial filtering due to self-phase modulation in a planar-oriented cell and nonlinear transmission between crossed polarizers in a twist-oriented cell. These processes do not require an external electric field. The substrates are arranged such that light propagates along the $+c$ axis in each substrate, allowing a secondary process of power transfer to occur through contradirectional photorefractive two-beam coupling. © 2006 Optical Society of America
OCIS codes: 250.0230, 160.3710, 230.3720.

$\text{LiNbO}_3\text{:Fe}$ is capable of producing a bulk electric field^{1,2} on the order of 140 kV/cm. Upon illumination, an asymmetrical potential associated with this material causes the photoionized electrons to move in a preferential direction, generating a photoinduced current and subsequent electric field in the region of light known as the photovoltaic (PV) field. We propose a hybridized liquid-crystal (LC) arrangement utilizing the PV field to activate a LC. The arrangement consists of a LC layer between two $\text{LiNbO}_3\text{:Fe}$ substrates. When illuminated, the PV field in each substrate creates a field between the two substrates sufficient to reorient the LC molecules; therefore an external electric field is not necessary. The cell can be constructed with planarly aligned LC molecules, to create a spatial filter due to transverse phase modulation of the beam,³⁻⁵ or with a twisted nematic alignment, to create a PV light valve when the cell is placed between crossed polarizers. In the latter case the rotation in polarization experienced by the incident beam is disrupted by the PV field-induced reorientation of the LC, reducing the transmitted power when the cell is placed between crossed polarizers.

In addition to being PV, $\text{LiNbO}_3\text{:Fe}$ is also a photorefractive material. This makes contradirectional two-beam coupling (TBC) possible when two mutu-

ally coherent counterpropagating beams couple through the recording of a reflection grating.⁶⁻⁸ Power transfer occurs in a single direction determined by the signs of the charge carriers and the effective electro-optic coefficient for a given crystal orientation.⁹ In the self-pumped TBC configuration a transfer of power occurs between the pump beam and a Fresnel-reflection-generated signal beam from the rear surface of the crystal.¹⁰⁻¹² The crystal c axis is oriented such that the signal beam is amplified at the expense of the pump beam. To take advantage of the photorefractive effect, the $\text{LiNbO}_3\text{:Fe}$ substrates are arranged such that light propagates along the c axis, allowing TBC to take place in each substrate while the PV field simultaneously activates the LC.

The substrates used for this study were 25.4 mm $\times$ 25.4 mm $\times$ 1.0 mm $\text{LiNbO}_3\text{:0.05 mol \% Fe}_2\text{O}_3$ crystals, where the thickness along the c axis was 1.0 mm. The c surfaces of each crystal were optically polished and spin coated with a rubbing layer consisting of a mixture of 0.125 wt. % Elvamide in methanol and were rubbed for planar alignment. Elvamide is a methanol soluble nylon multipolymer resin (DuPont). Each cell was constructed by using 20 μm spacers and was filled with TL205 (Merck), a highly resistive low-ionic LC, reducing the effects of

screening charges that may result from a more ionic LC. At 589 nm and 20°C, Merck reports an ordinary index of 1.527 and a Δn of 0.217 for TL205.¹³ To describe the behavior of the photorefractive substrates, data were also taken in the absence of the LC. For these experiments the cell was filled with an index-matching fluid of $n=1.7$, simulating any reduction in etalon effects resulting from the presence of the LC. The spatial filters were constructed with the LiNbO₃:Fe substrates rubbed antiparallel, while the substrates for the PV light valves were rubbed orthogonally to one another to produce a twist in the LC alignment. This longitudinal twist induces a rotation in the polarization of incoming light, which is disrupted by the reorientation of the LC when the system is subject to optical radiation.

The experimental arrangement is shown in Fig. 1. The pump beam, at a power of 1 mW originating from a continuous-wave 532 nm intracavity frequency doubled YVO₄:Nd laser (Coherent Verdi-5), was focused within the LC layer at an optimum position corresponding to the shortest response time. A 100 mm focal length plano-convex lens at $\approx f/30$ was used, yielding a $1/e$ diameter of $\approx 20 \mu\text{m}$ at the focal plane. The pump beam, polarized parallel to the rubbing direction of the LC cells, propagated along the positive c axes of each substrate. The c -axis absorption coefficients were approximately 1.53 cm^{-1} for each substrate. A photodiode and an oscilloscope were used to monitor the transmitted laser power for a 5.5° full cone angle. A polarizer oriented orthogonally to the polarization of the incident laser beam was placed after the sample for measurements involving crossed polarizers.

Results for self-phase modulation in a hybridized planar cell are shown in Fig. 2(a). The vertical dotted lines divide the plot into three regions. In the absence of the LC, a steady decrease in transmitted power is seen as a result of TBC in the photorefractive substrates. However, with the addition of the LC a much faster reduction in transmitted power is initially observed, as seen in region 1 of Fig. 2(a). This is attributed to a lensing effect that occurs as a result of the Gaussian profile of the incident beam intensity. A buildup of charges on the surfaces of the LiNbO₃:Fe substrates occurs as the PV field builds up in each substrate. The buildup of charges and the subsequent field across the LC layer is initially strongest in the center of the Gaussian beam, where the beam is most intense, so there is a greater influence on the

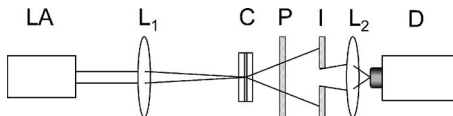


Fig. 1. Experimental arrangement used for testing the PV field-induced reorientation of hybridized cells. The pump beam, originating from a 532 nm laser (LA), was focused onto the hybridized cell (C) using a 100 mm focal length plano-convex lens (L_1). The transmitted power with a cone angle determined by the iris (I) was focused onto the detector (D) by using a collection lens (L_2). A polarizer (P) oriented orthogonally to that of the incident laser polarization was used for experiments involving crossed polarizers.

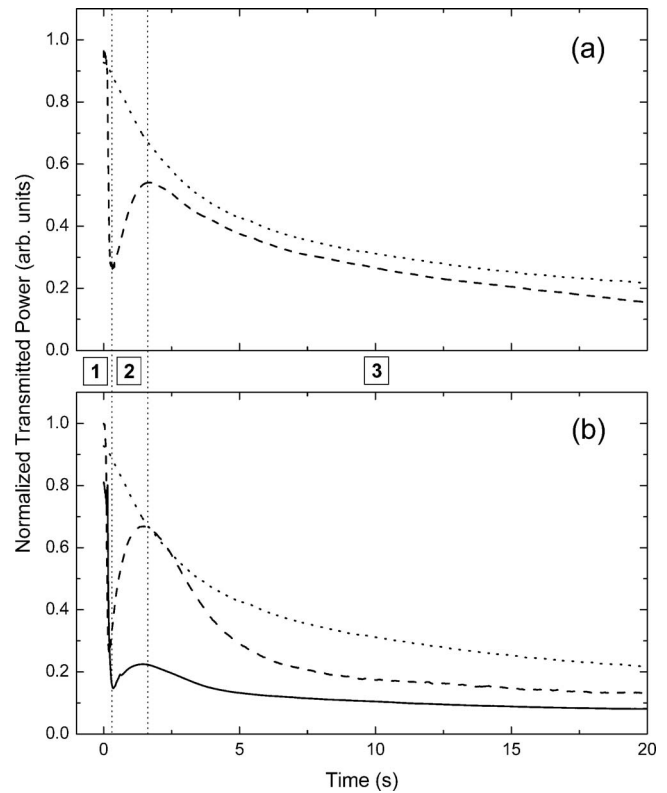


Fig. 2. Transmitted power for (a) the hybridized spatial filter and (b) the PV light valve. The transmitted power in the absence (dotted curve) and presence (dashed curve) of the LC is given for both cells. Results for the PV light valve when placed between crossed polarizers are also shown (solid curve).

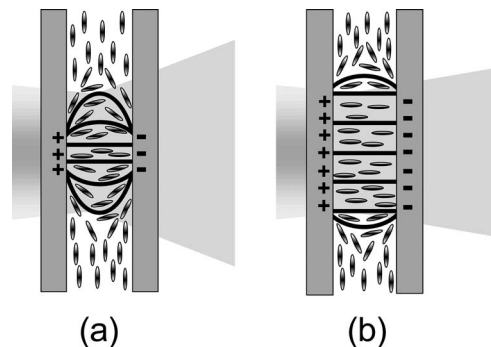


Fig. 3. The shaded region represents the portion of the cell illuminated by a laser beam propagating from left to right. (a) In the transient regime, the Gaussian profile of the incident light initially results in a graded index of refraction. (b) As a steady state is reached, surface charges gradually build up on the substrates in the less intense edges of the incident Gaussian beam, strengthening the field in this region.

LC orientation here than at the edges of the beam. This is depicted in Fig. 3(a), where the shaded region represents the portion of the cell illuminated by the laser beam. Because the LC molecules are reoriented to varying degrees across the inhomogeneous region of illumination, the incident light experiences a graded index of refraction, and the LC acts as a lens to strongly diverge the incident light. This is perceived as a decrease in the transmitted power reaching the detector. However, the surface charges gradu-

ally build up in the less intense edges of the beam, inducing a more complete reorientation of the LC molecules throughout the illuminated region. As depicted in Fig. 3(b), this results in a loss of the graded index of refraction, thereby disrupting the lensing effect and reducing the divergence of the transmitted beam. This accounts for the subsequent increase in transmitted power reaching the detector observed in region 2 of Fig. 2. The reduction in transmitted power observed in region 3 is a result of the TBC occurring in the $\text{LiNbO}_3\text{:Fe}$ substrates. Cells constructed with glass substrates showed no response, ruling out any contribution from the LC nonlinear effect.

Results for the PV light valve are seen in Fig. 2(b). In the absence of the LC, a steady decrease in transmitted power is seen as a result of TBC in the photorefractive substrates. In the presence of the LC, a lensing effect diverges the incident light, resulting in the sudden decrease in transmitted power seen in region 1 of Fig. 2(b). However, in this configuration the reorientation of the LC also disrupts the longitudinal twist, and the incident beam does not experience a rotation in polarization as it propagates through the cell. The presence of an output polarizer oriented orthogonally to the polarization of the incident light allows for birefringent switching, causing the cell to function as a light valve. Absorption by the polarizer was measured and taken into account. Because of the Gaussian nature of the incident beam, the longitudinal twist is more strongly disrupted in the center of the beam where the PV field is the strongest. While the buildup of surface charges on the $\text{LiNbO}_3\text{:Fe}$ substrates in the edges of the incident beam results in a loss of the lensing effect, it also further prevents the rotation of polarization in the edges of the beam. In the absence of the output polarizer, only the lensing effect is seen, and the transmitted power reaching the detector increases in region 2. However, in the presence of crossed polarizers, the buildup of surface charges allows more of the transmitted beam to be polarized orthogonally to that of the output polarizer,

accounting for the less significant increase in transmitted power reaching the detector in region 2 of Fig. 2(b). Although the crossed polarizers would completely block the transmitted light in principle, this outcome is prevented as natural leakage of the surface charges prevents a complete disruption in the twist of the LC alignment, particularly at the edges of the beam. Additional light leakage occurs when photorefractive noise, which is generated within the lithium niobate windows,¹⁴ results in random polarization states of the output beam. The reduction in power observed in region 3 of Fig. 2(b) is again a result of the ongoing TBC occurring in the substrates.

*Corresponding author, e-mail address dean.evans@wpafb.af.mil.

References

1. G. Cook, J. P. Duignan, and D. C. Jones, *Opt. Commun.* **192**, 393 (2001).
2. A. M. Glass, D. von der Linde, and J. Negran, *Appl. Phys. Lett.* **25**, 233 (1974).
3. S. D. Durbin, S. M. Arakelian, and Y. R. Shen, *Opt. Lett.* **6**, 411 (1981).
4. I. C. Khoo, J. Y. Hou, T. H. Liu, P. Y. Yan, R. R. Michael, and G. M. Finn, *J. Opt. Soc. Am. B* **4**, 886 (1987).
5. J. J. Wu, S. H. Chen, J. Y. Fan, and G. S. Ong, *J. Opt. Soc. Am. B* **7**, 1147 (1990).
6. Y. H. Ja, *Opt. Quantum Electron.* **14**, 547 (1982).
7. P. Yeh, *Opt. Commun.* **45**, 323 (1983).
8. K. R. McDonald, J. Feinberg, Z. Z. Ming, and P. Günter, *Opt. Commun.* **50**, 146 (1984).
9. J. Y. Chang, C. R. Chinjen, S. H. Duan, C. Y. Huang, and C. C. Sun, *Appl. Phys. Lett.* **72**, 2199 (1998).
10. I. F. Kanaev, V. K. Malinovski, and B. I. Sturman, *Sov. Phys. JETP* **47**, 834 (1978).
11. A. Krumins, Z. Chen, and T. Shiosaki, *Opt. Commun.* **117**, 147 (1995).
12. G. Cook, D. C. Jones, C. J. Finnan, and A. W. Vere, in *Proc. SPIE* **3798**, 2 (1999).
13. Merck, datasheet for Licrilit Products.
14. D. R. Evans, J. L. Carns, S. A. Basun, M. A. Saleh, and G. Cook, *Opt. Mater.* **27**, 1730 (2005).