

REPORT DOCUMENTATION PAGE

ADA202526

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) This optoelectronic workshop represents the fourth of a series of intensive academic/ government interactions in the field of advanced electro-optics as part of the Army sponsored University Research Initiative. The workshops are a collaboration between the Center for Opto-Electronic Systems Research at the University of Rochester, Rochester, New York and the U.S. Army Center for Night Vision and Electro-Optics, Ft. Belvoir, Virginia. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO-URI) and Dr. Rudy Buser, NVEOC.			
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The Center for Night Vision and Electro-Optics

OPTOELECTRONIC WORKSHOPS

IV

LIQUID CRYSTALS FOR LASER APPLICATIONS

May 11, 1988

sponsored jointly by

**ARO-URI Center for Opto-Electronic Systems Research
The Institute of Optics, University of Rochester**

OPTOELECTRONIC WORKSHOP

ON

LIQUID CRYSTALS FOR LASER APPLICATIONS

Organizer: ARO-URI-University of Rochester
and Center for Night Vision and Electro-Optics

1. INTRODUCTION
2. SUMMARY -- INCLUDING FOLLOW-UP
3. VIEWGRAPH PRESENTATIONS

A. Center for Opto-Electronic Systems Research
Organizer -- Stephen Jacobs

A Dozen Liquid Crystal Device Concepts
Stephen Jacobs

Nonlinear Optics and Laser Damage Resistance
of Liquid Crystals
Ansgar Schmid

Ferroelectric Liquid Crystals
Kenneth Marshall

B. Center for Night Vision and Electro-Optics
Organizer -- Juergen Pohlmann

Historical Perspective: Liquid Crystal Research
at Fort Belvoir
Wolfgang Elser

Current Liquid Crystal Research
Juergen Pohlmann

Liquid Crystal Electro-Optic Shutter
James Miller

4. LIST OF REFERENCES
5. LIST OF ATTENDEES
6. DISTRIBUTION



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Availability Codes	
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Dist. Statement	
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1. INTRODUCTION

This workshop represents the fourth of a series of intensive academic/government interactions in the field of advanced electro-optics, as part of the Army sponsored University Research Initiative. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO-URI) and Dr. Rudy Buser, NVEOC.

2. SUMMARY AND FOLLOW-UP ACTIONS

a. IR Light Scatterer:

Based upon viewgraphs provided by J. Miller and subsequent discussions, we will consider liquid crystal and other technologies which might have the required performance. We will discuss our concepts further with him to define, if possible some activity which we might jointly pursue (within our resource base) to construct and characterize an alternative device concept.

b. Optical Power Limiter:

Perhaps Night Vision and Electro-Optic Center wants to organize a more narrowly defined meeting to address their specific needs compared to objectives already being pursued by the NADC and the BAA. We would be happy to help organize and participate in such a meeting.

c. Holographic Photopolymer:

We will obtain more information from Dr. Thomas Stone (U of R) to see if there is some input we can make to the doping of liquid crystals into porous polymer films. Mark Norton (NV&EOC) has an interest in this.

CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH
A DOZEN LIQUID CRYSTAL DEVICE CONCEPTS

A Dozen Liquid-Crystal Device Concepts

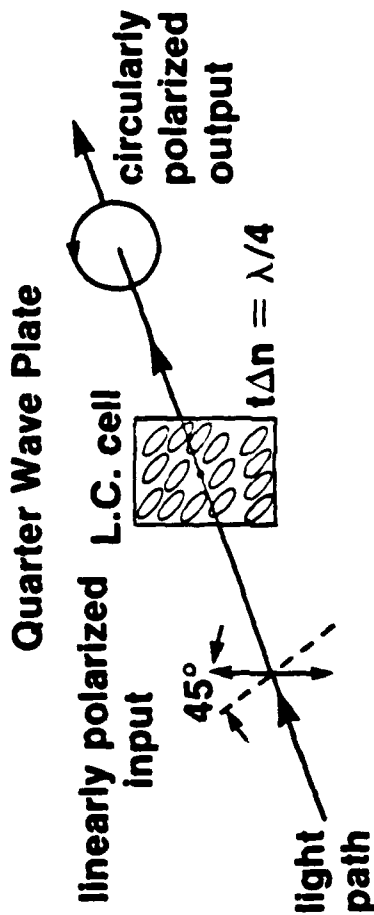


- | | |
|-------------------|-------------------------------|
| (1) Wave Plate | (7) Attenuator |
| (2) Polarizer | (8) Beam Apodizer |
| (3) Isolator | (9) (Bistable) Beam Deflector |
| (4) Beam Splitter | (10) Shutter/Chopper |
| (5) Mirror | (11) Power Limiter |
| (6) Notch Filter | (12) Light Scatterer |

G2299

Nematic Class: Device Application True Zero-Order Wave Plates

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MgF₂
Mica Quartz
Sapphire Plastics

Properties of Interest

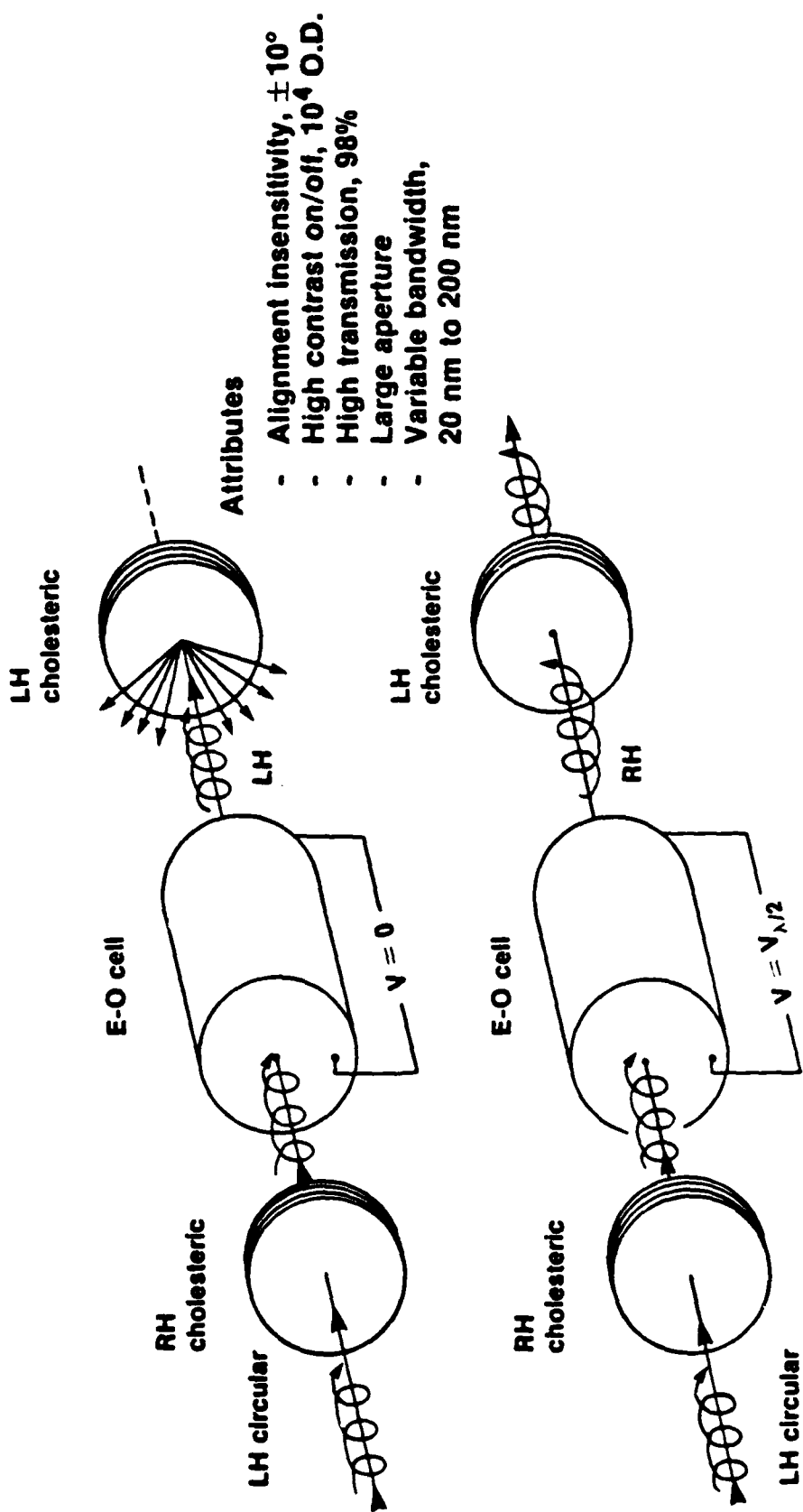
Liquid Crystals

- Spectral transmission UV-IR
- Refractive index 1.45-1.80
- Birefringence 0.035-0.280
- Thickness for $\lambda/2$ plate 1-4 μm
- Accuracy of retardance $\pm 1\%$ with blending
- Uniformity of retardance ± 1.5 nm across 100 mm
- Angular sensitivity weak
- Laser-damage resistance $> 6 \text{ J/cm}^2$ (1 ns, 1000 nm)
- Optical quality substrate defined
- Aperture limits none

G2300

Circular Polarizer for Pockels' Cell, E-O Switching

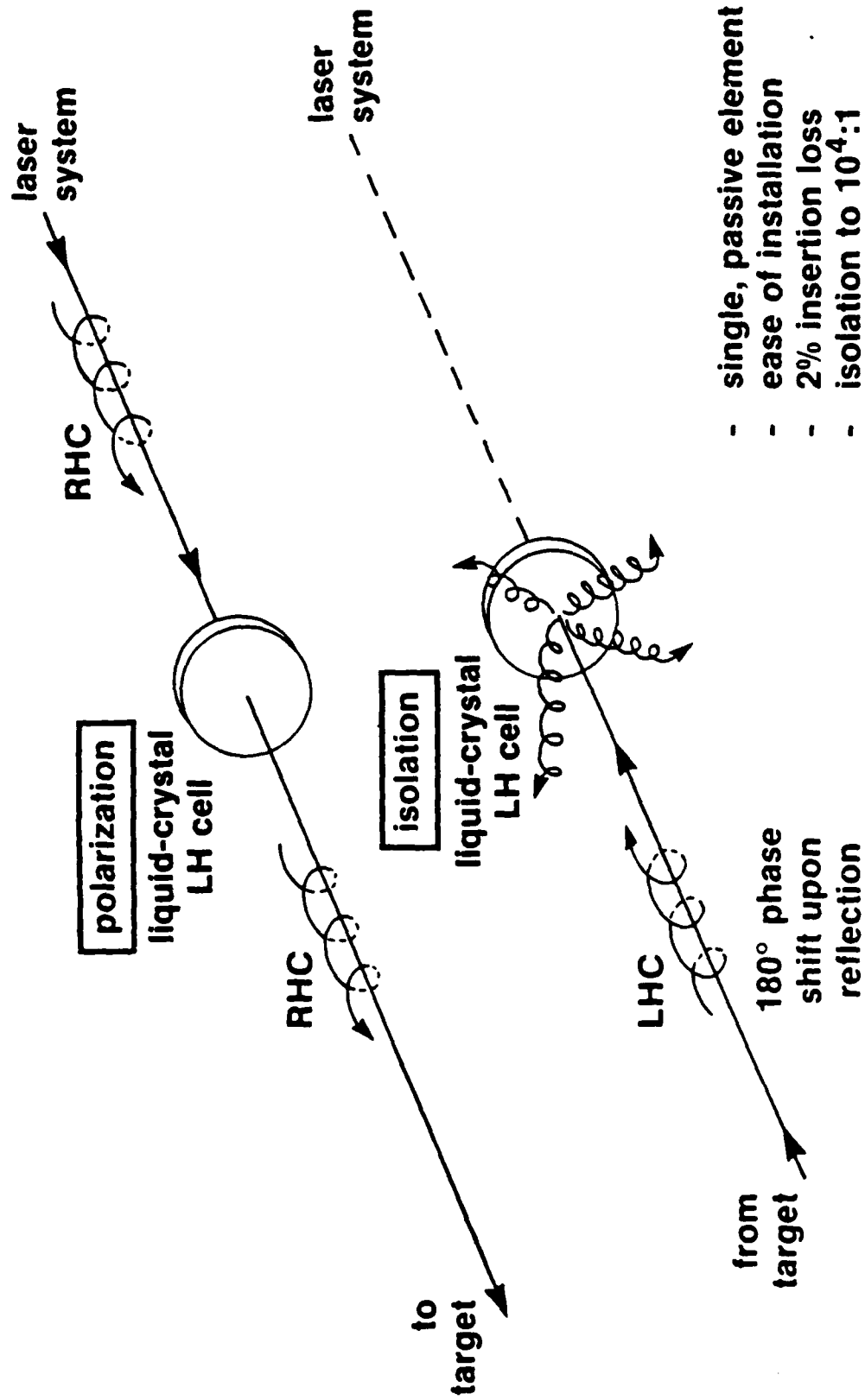
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Dual Role for Liquid-Crystal Polarizers: Polarization and Isolation

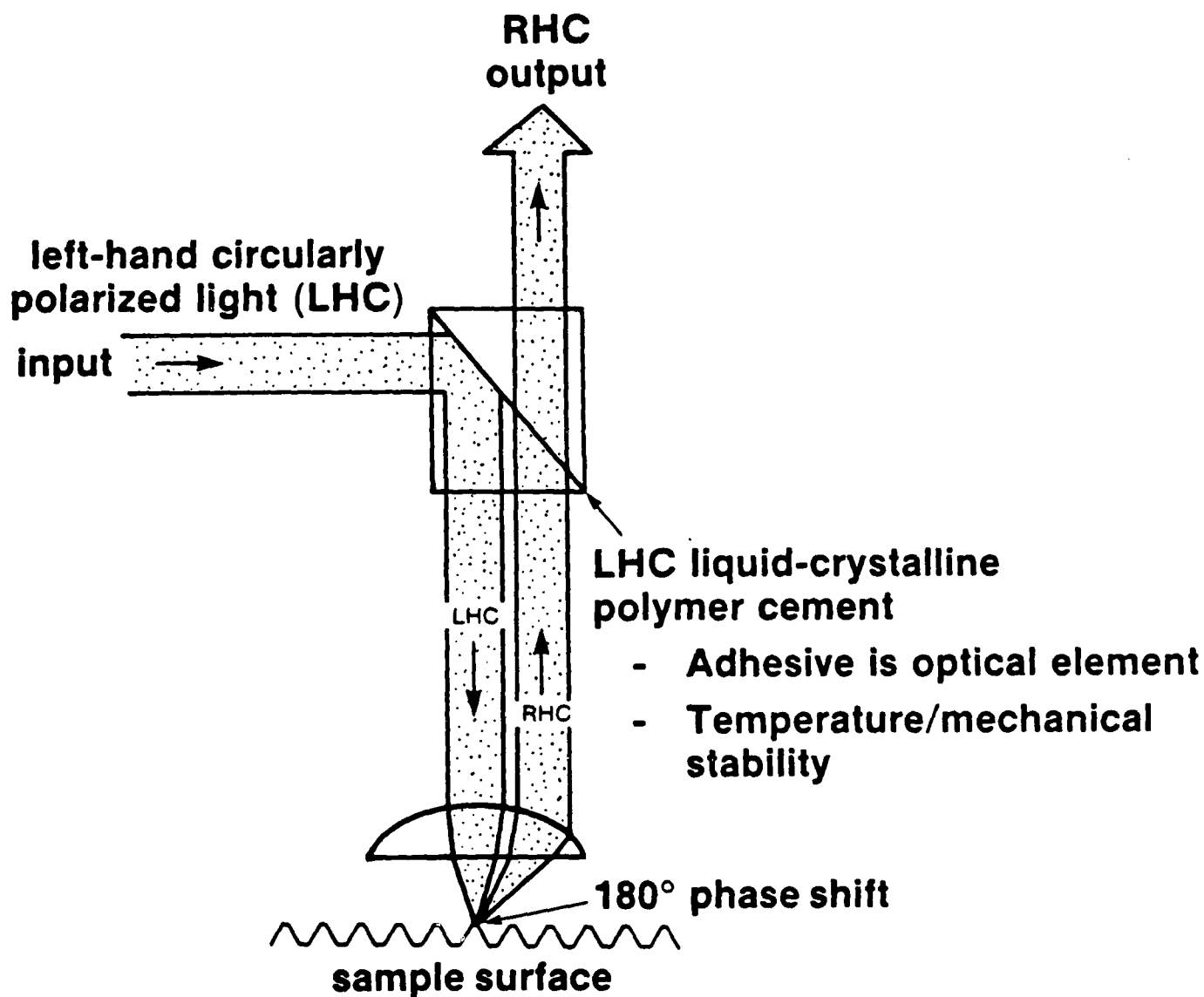
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- single, passive element
- ease of installation
- 2% insertion loss
- isolation to $10^4:1$

Beam-Splitter Liquid-Crystal-Polarizing Prism

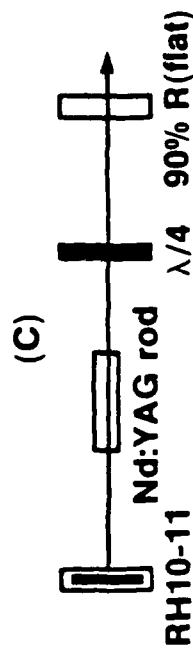
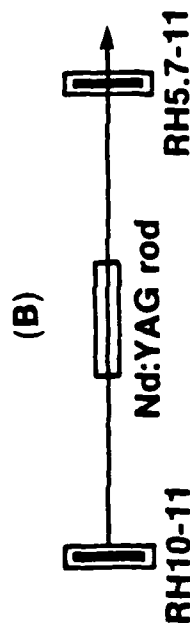
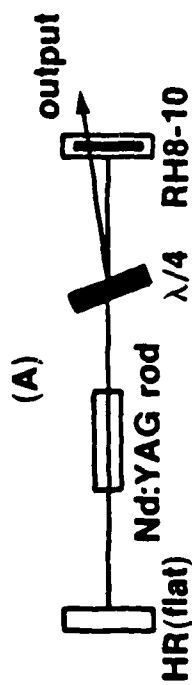
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Liquid-Crystal Mirror Laser Resonator Configuration

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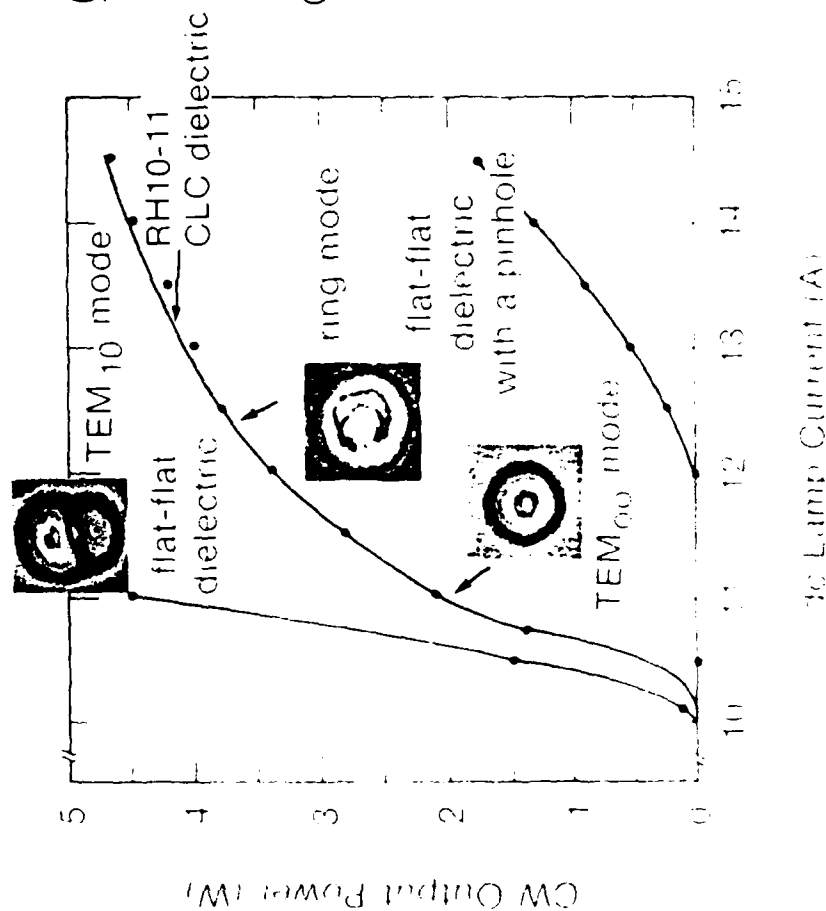


- Modification to a Control Laser Corp. model 256 Nd:YAG head (cw)

- (A) CLC (thick)-dielectric: output via Fresnel reflection
- (B) CLC (thick)-CLC (thin): output through thin partial reflector demonstrated
- (C) CLC (thick)-dielectric: output through 90% R

- Performance improvements
 - TEM₀₀ output without pinhole
 - Reduced angular sensitivity

Comparison of CLC Resonator with Dielectric Resonator



(flat-flat) dielectric resonator

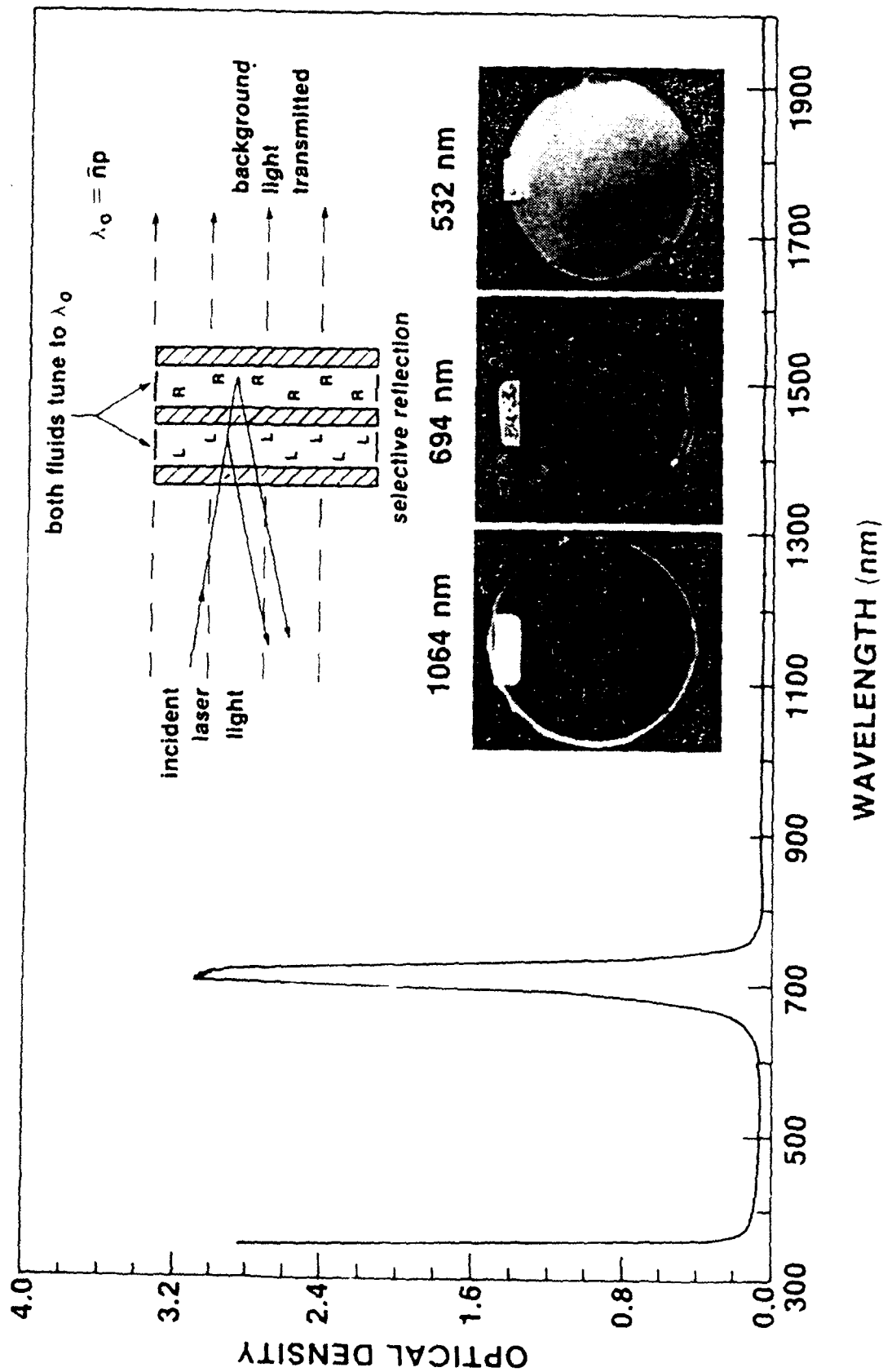
- multimode output profile with no internal aperture
- high sensitivity to mirror tilt (~ 0.8 arcsec)

CLC-dielectric resonator

- TEM₀₀ mode operation with no internal aperture
- low sensitivity to mirror tilt (~ 1.8 arcsec)

LIQUID-CRYSTAL LASER-BLOCKING FILTER

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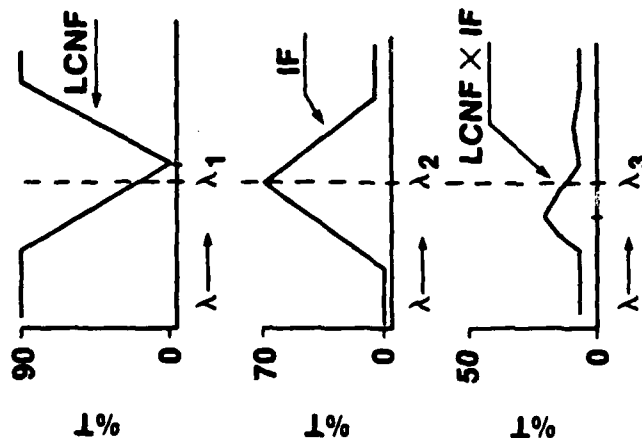
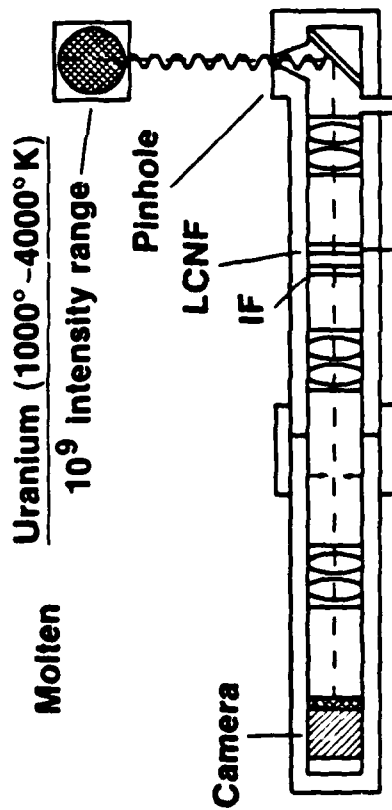
Optical Radiation Attenuator

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LLS

United States Patent [19] [11] Patent Number: 4,726,660
Rushford [45] Date of Patent: Feb. 23, 1988

[54] TECHNIQUE FOR COMPRESSING
LIGHT INTENSITY RANGES
UTILIZING A SPECIFICALLY
DESIGNED LIQUID-CRYSTAL
NOTCH FILTER

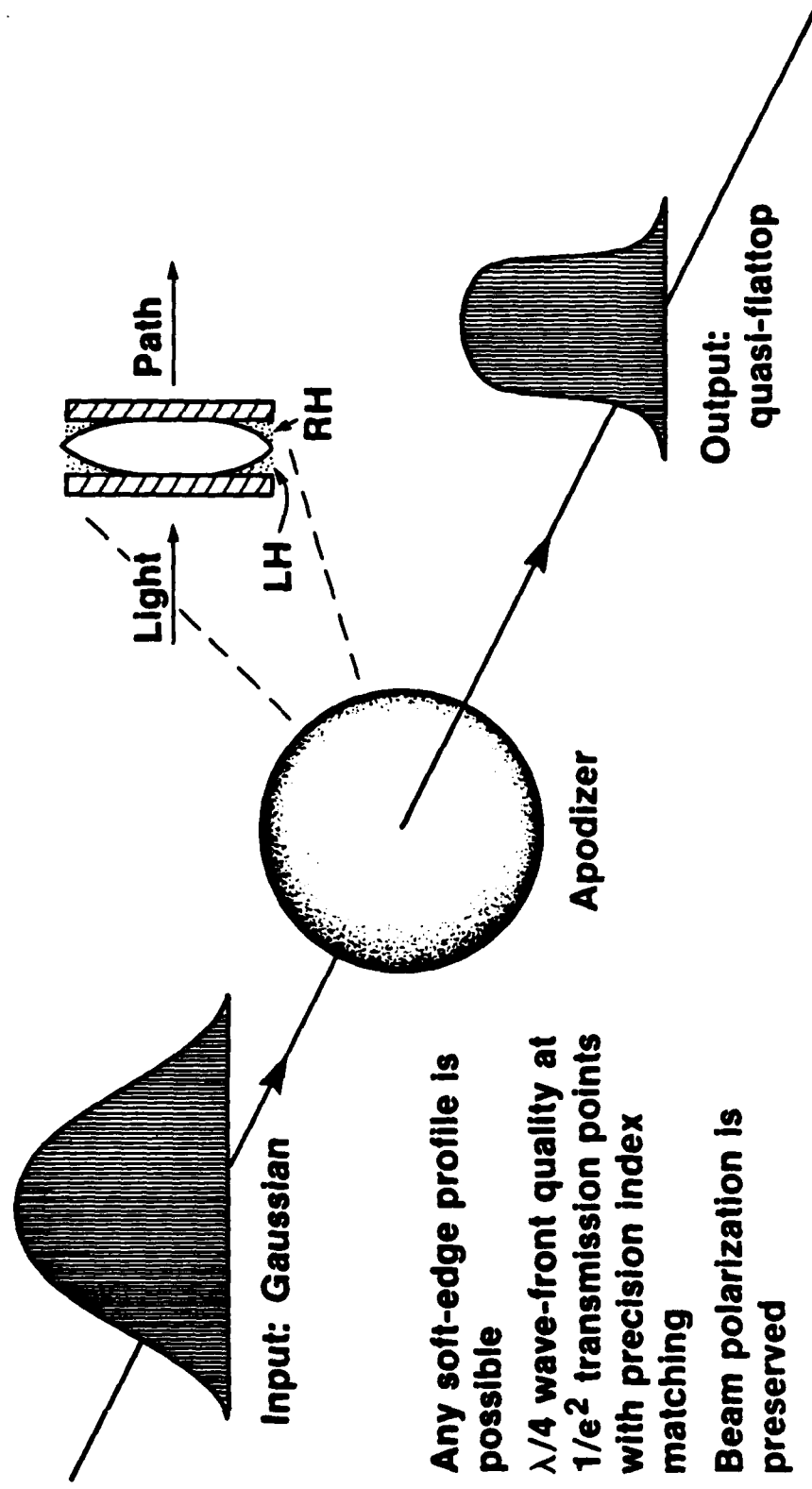
[75] Inventor: Michael C. Rushford, Livermore, CA



G2303

Liquid-Crystal Laser Beam Apodizers

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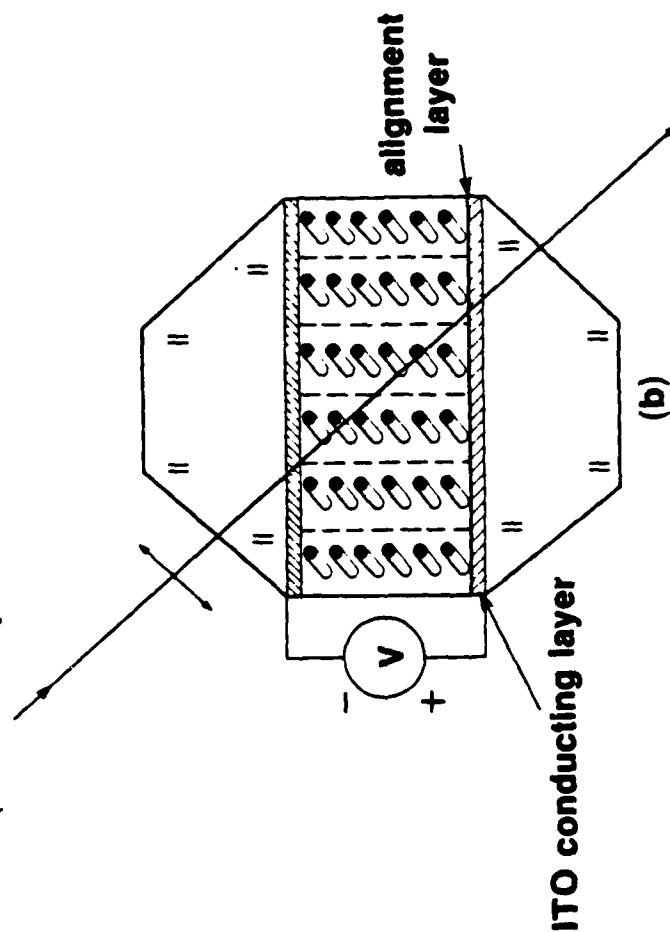
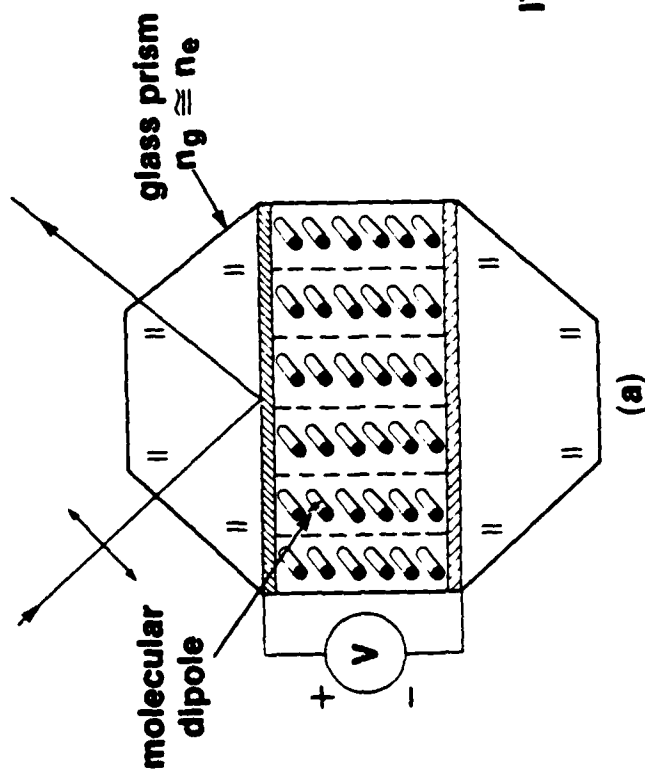


- Any soft-edge profile is possible
- $\lambda/4$ wave-front quality at $1/e^2$ transmission points with precision index matching
- Beam polarization is preserved

Two-Position Bistable Beam Deflection Device Using FTIR in Ferroelectric Chiral Smectic C Mesogens

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Incident Polarization Orientation (45° out of plane of drawing)

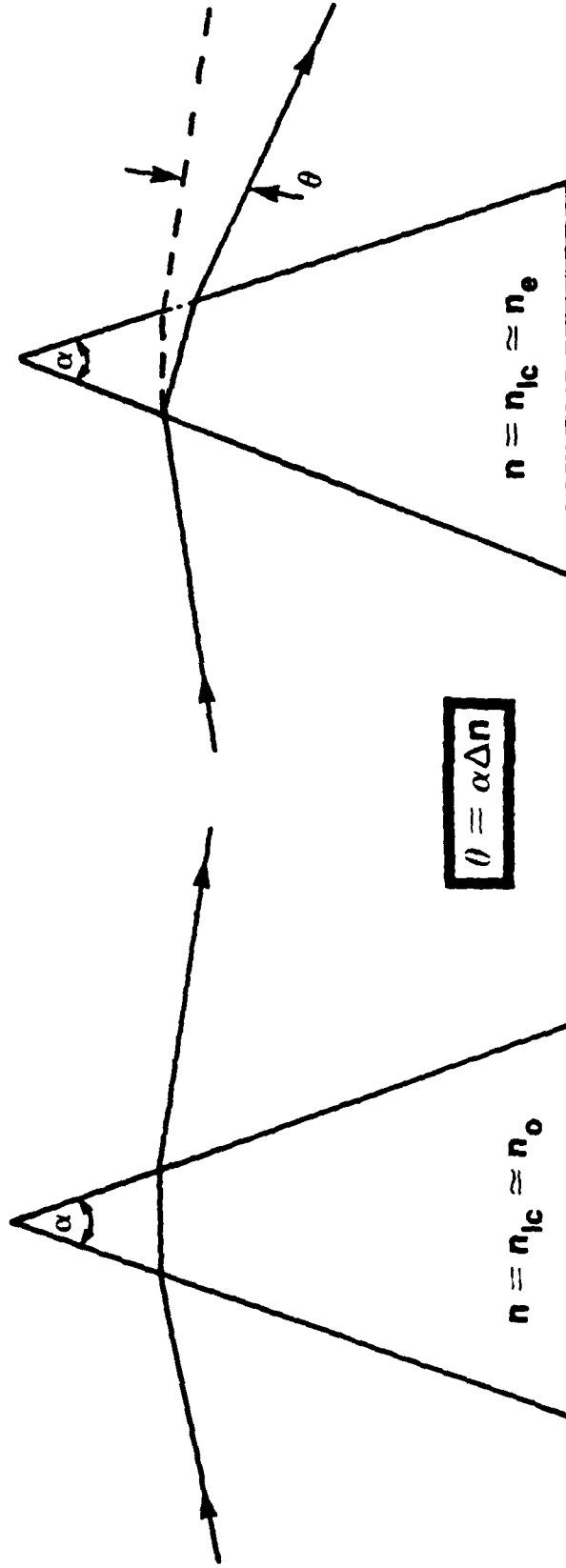


(a) Incident radiation experiences n_o , allowing TIR. (b) Reversal of field polarity causes incident radiation to experience n_e , resulting in FTIR.

Liquid-Crystal Wedge Multiposition Beam Deflector Concept



- Several possible modes of operation
 - bistable
 - bistable with tunable birefringence around two bistable positions
 - nonbistable



where θ = deflection angle (several tenths of a degree)

α = cell wedge angle (0.1-1.0 degrees)

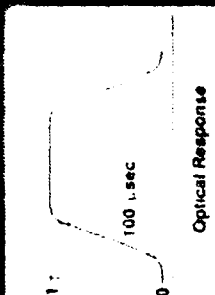
Δn = change in refractive index due to field-induced director reorientation (as large as 0.2)

Ferroelectric Liquid-Crystal Shutter/Chopper

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A High Speed Light Valve System



Optical Response

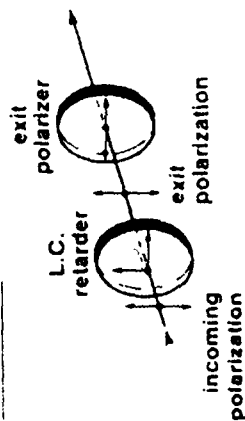
100 μsec

- Liquid crystal — no moving parts
- High speed shutter/chopper

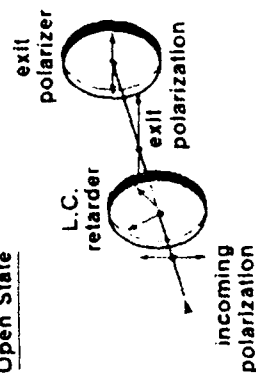


Meadowlark
Optics

Closed State



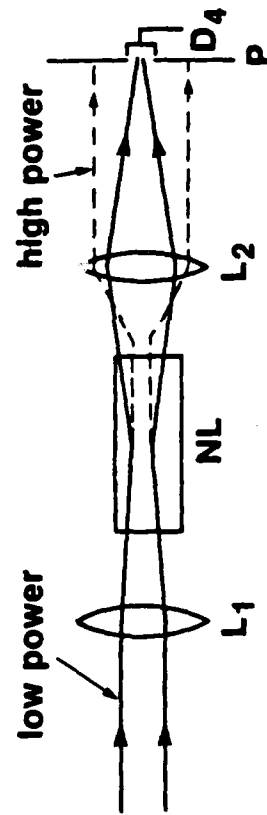
Open State



Optical Power Limiter Geometries

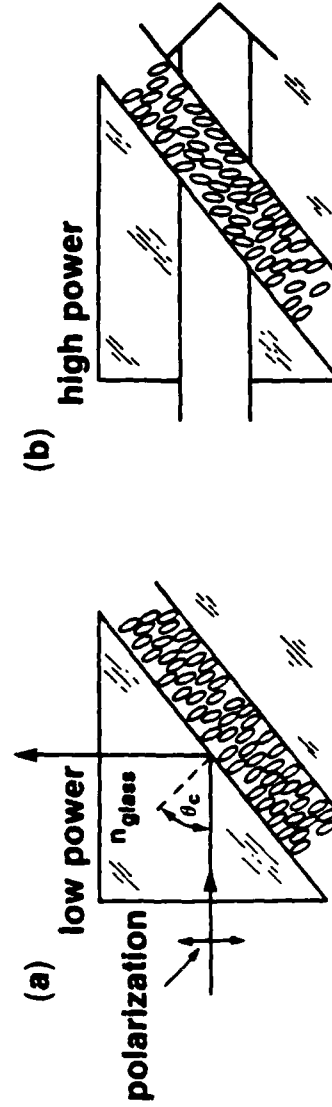
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LLE

- Self Focusing



• After Solleau et al., *IEEE J. Quantum Electron.* QE-19, 731 (1983).

- Total Internal Reflection



Polymer-Dispersed Liquid Crystals Induced Light Scattering

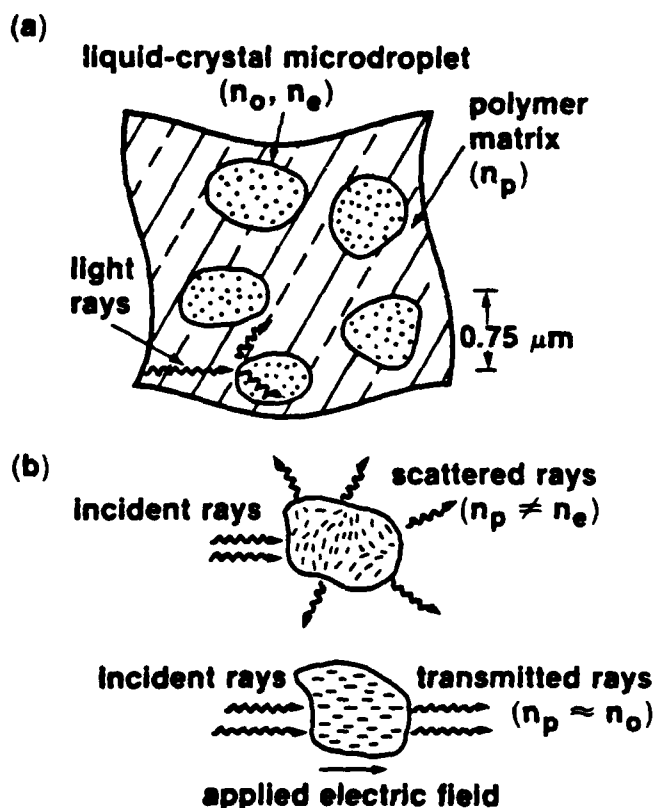


United States Patent [19]
Ferguson

[11] Patent Number: 4,556,289
[45] Date of Patent: Dec. 3, 1985

[54] LOW BIREFRINGENCE
ENCAPSULATED LIQUID CRYSTAL
AND OPTICAL SHUTTER USING
SAME

[75] Inventor: James L. Ferguson, Kent, OH



From N. A. Vaz and G. P. Montgomery, Jr.,
J. Appl. Phys. **62**, 3161 (1987).

CLEO
TUESDAY, 26 APRIL 1988
Anaheim Convention Center

**TuT, Light Manipulation with
New Materials**

4:30 PM

**TuT1 Observation of Optical
Limiting Using Polymer-
Dispersed Liquid-Crystal Thin
Films,**

David M. Pepper, J. David
Margerum, Anna M. Lackner,
Elena Ramos, *Hughes Research
Laboratories*. Optical limiting
using polymer-dispersed liquid
crystals is demonstrated. These
heterogeneous mixtures are
index matched at low intensities,
and behave as diffuse scatterers
in the nonlinear regime due to
optical reorientation of the
liquid-crystal dispersant.

CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH
NONLINEAR OPTICS AND LASER DAMAGE RESISTANCE OF LIQUID CRYSTALS

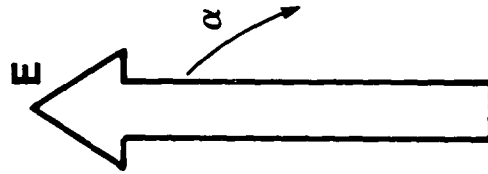
Two Dominant Physical Mechanisms for Third-Order Optical Nonlinearities in Liquid Crystals

UR
LLE

- **Orientational**
based on large birefringence: $\Delta n = 0.1-0.2$
- **Electronic**
based on electron delocalization

G2309

Linearly polarized external field induces torque

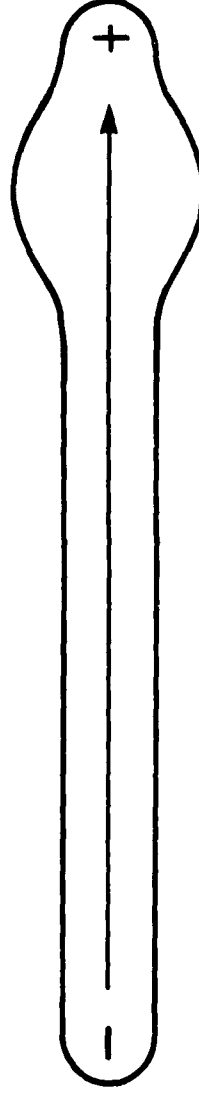


**Result: Field-driven molecular reorientation
(Freedericksz effect)**

Mechanism of Orientational Optical Nonlinearity in Liquid Crystals

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Donor/acceptor (substituent) pairs on liquid-crystal core
introduce electric dipole moment



The Dynamics of the Freedericksz Transition Is Driven by the External Forces and Elastic Restoring Forces



- Free energy density:

$$F = \int_V d\mathbf{r} \left\{ \kappa_{11} (\nabla \cdot \vec{n})^2 + \kappa_{22} [\vec{n} \cdot (\nabla \times \vec{n})] + \kappa_{33} (\vec{n} \times \nabla \times \vec{n})^2 \right. \\ \left. + (\vec{E} \cdot \vec{D} + \vec{B} \cdot \vec{H}) \right\}$$

elastic part electromagnetic part

- Maxwell:

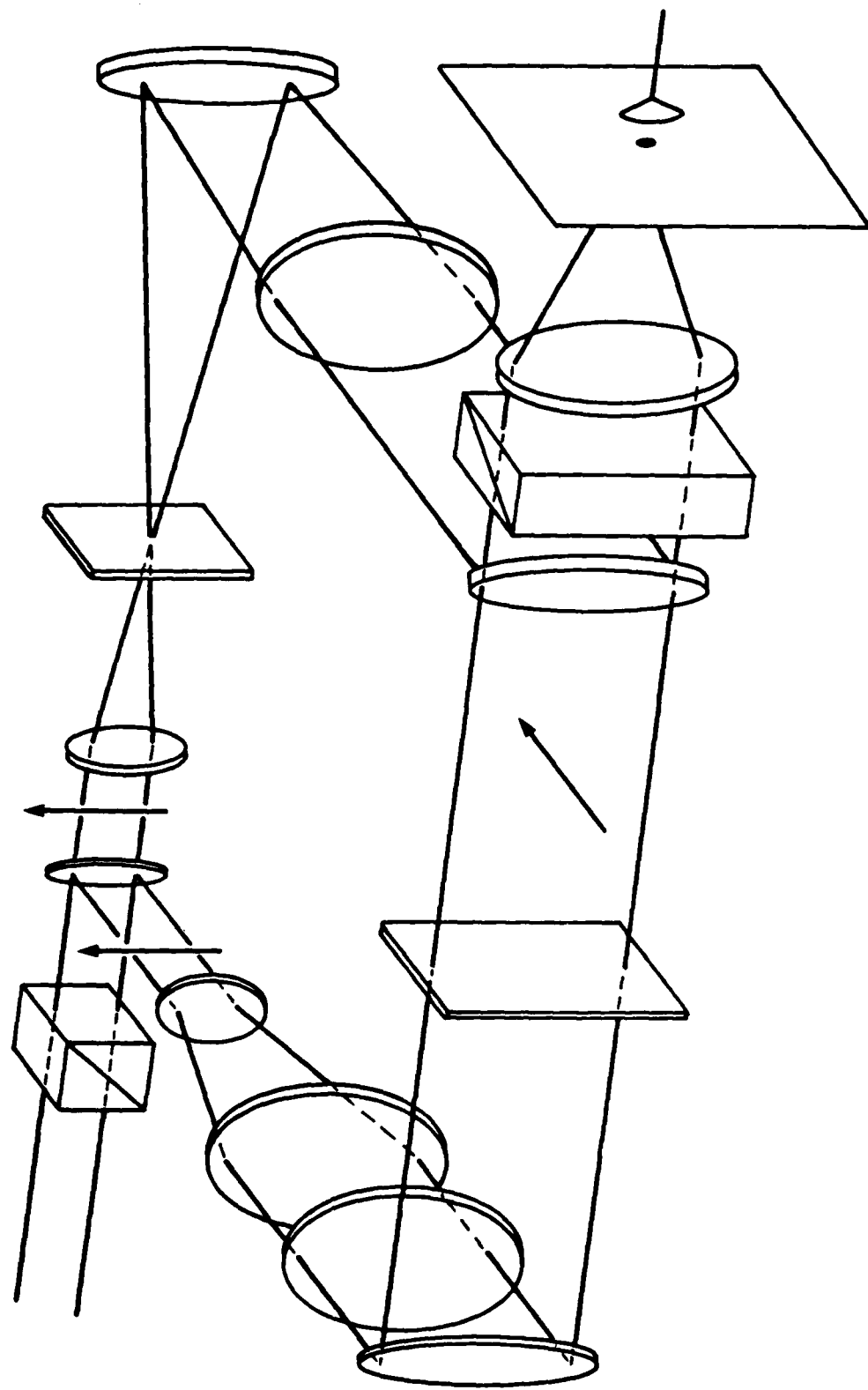
$$\vec{D} = \epsilon(\alpha) \vec{E}$$

- Euler-Lagrange:

$$\delta^2_{xx} \alpha + \delta^2_{zz} \alpha + A \frac{\sin \alpha \cos \alpha}{(1 - B \sin^2 \alpha)^{3/2}} = 0$$

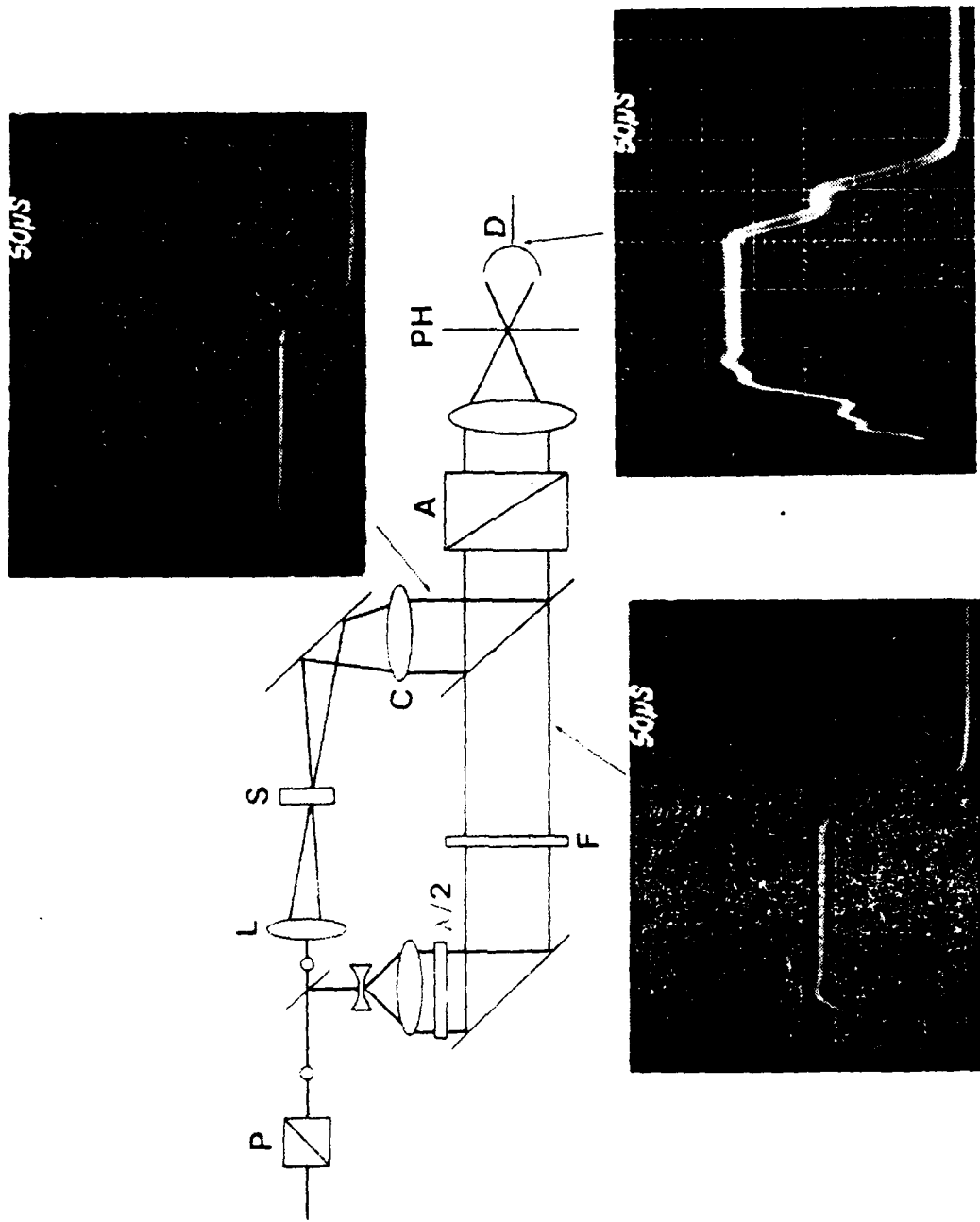
Mach-Zehnder Interferometer for Self-Phase-Modulation Measurements in Thin Liquid-Crystal Cells

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Temperature-Induced Phase Separation in Homeotropic, Smectic-A Octyl-Cyanobiphenyl

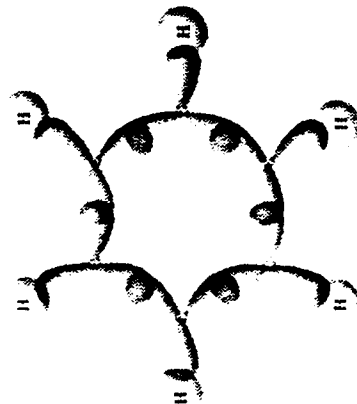
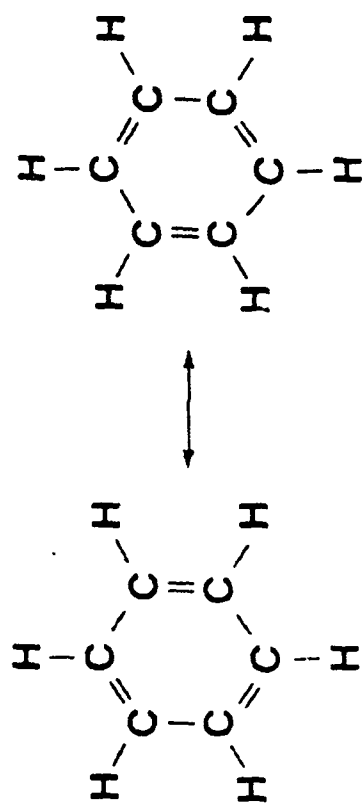
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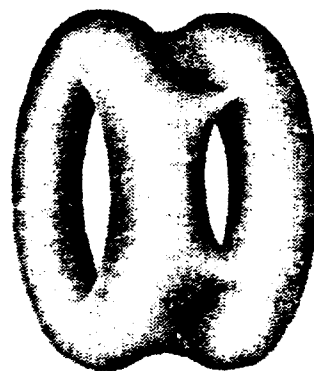
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Delocalized Orbitals in Aromatic Systems

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δ
Bonded

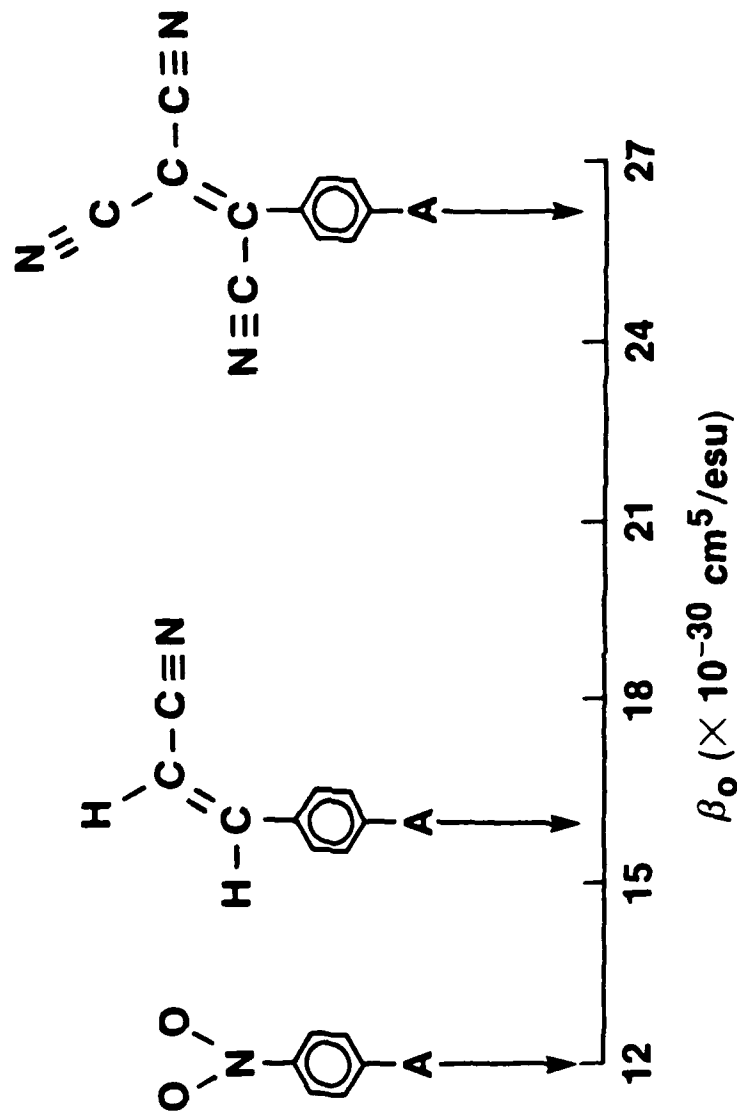


π
Bonded

Electronic Molecular Hyperpolarizability Is Strongly Enhanced by π -Electron Delocalization

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Second-Order Example:
frequency conversion at $1.3 \mu\text{m}$
(AT&T Bell Laboratories)



We Demonstrate The Link Between 1053-nm Laser Damage and Degree of Conjugation in Liquid Crystals



- Use both monomeric and polymeric systems
- Prepare samples of identical pathlength ($\sim 100 \mu\text{m}$)
- Monitor impurity trace levels
- Limit use of alignment layers
- Test at identical wavelength and pulse length

G2315

Fully Saturated Electron System Raises 1053-nm Damage Threshold in Liquid Crystals



Damage Threshold Comparison of Two Model Compounds
(800-ps pulse length, 100-μm path length, 5-mm spot size, linear polarization)

Compound	K-15	ZLI-1185
Structure	<chem>CCCCCCCCc1ccc(cc1)C#N</chem>	<chem>CCCCCCCCc1ccc(cc1)C#N</chem>
Mesophase	nematic (22°C)	nematic (62°C)
1-on-1 (J/cm ²)	9.6±2.4	>16.6*
N-on-1 (J/cm ²)	5.4±1.3	14.6±0.5

- Liquid crystals unaligned; alignment layers usually lower threshold
- *for given spot size, transport optics damage at 20 J/cm²

Summary



- Large, moderate-speed optical nonlinearities available through Freedericksz reorientation in liquid crystals
- When laser damage is a potential problem, choose organic materials that are highly saturated (free of conjugated bonds)
- There may be trade-offs between high damage threshold and other optical, mechanical or thermal properties
- Measured damage thresholds compare well with those of standard coatings

G2321

**CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH
FERROELECTRIC LIQUID CRYSTALS**

Presentation Format



- **Background-dielectric E-O effects in nematic liquid crystals**
- **Origin of ferroelectric E-O effects in chiral smectic liquid crystals**
- **Current status of ferroelectric liquid-crystal device technology**
- **Materials considerations for ferroelectric liquid-crystal devices**

Electro-Optic Devices Based on Dielectric Effects in Nematic Liquid Crystals



- **Wide application in information display area**
 - low operating voltage
 - low power consumption
 - relatively easy to fabricate
 - good contrast in strong ambient lighting
- **Disadvantages for high-speed optical processing/switching applications**
 - slow response times (10-500 ms)
 - static electric field required to reorient and stabilize director (not bistable)
 - electro-optic response not field linear (strong threshold effect)

Ferroelectric Liquid Crystals Advantages



- **Fast response - $0.5 \mu\text{s}$ demonstrated, nanosecond response times predicted**
- **Bistable switching effect - pulsed dc drive**
- **Optic axis orientation determined by polarity of applied electric field**
- **Field-linear E-O response possible under certain conditions**
- **Large E-O response for thin cell spacings**

G2319

Classification of Ferroelectric Smectic Phases



GROUP I: Smectic Liquid Crystals (C^* , I^* , F^*)

- No long-range periodic ordering
- Smectic C^* : random ordering within layer
- Smectic I^* and F^* : hexagonal close packed within layer

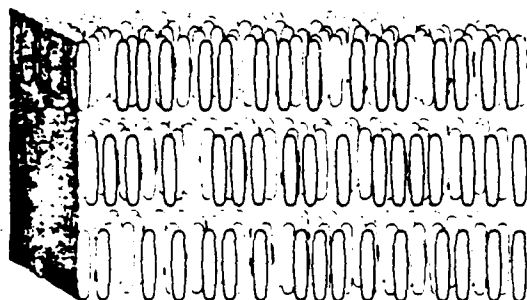
GROUP II: Anisotropic plastic crystals (J^* , G^* , K^* , and H^*)

- Long-range ordering of molecules in three dimensions

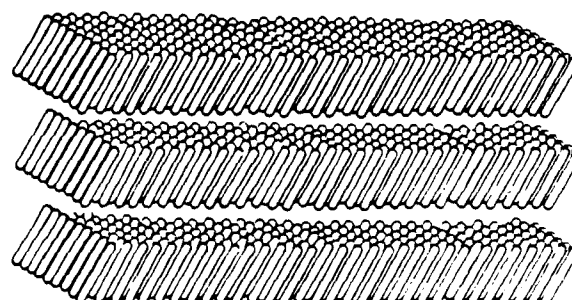
G1930

Structures in Smectic Class

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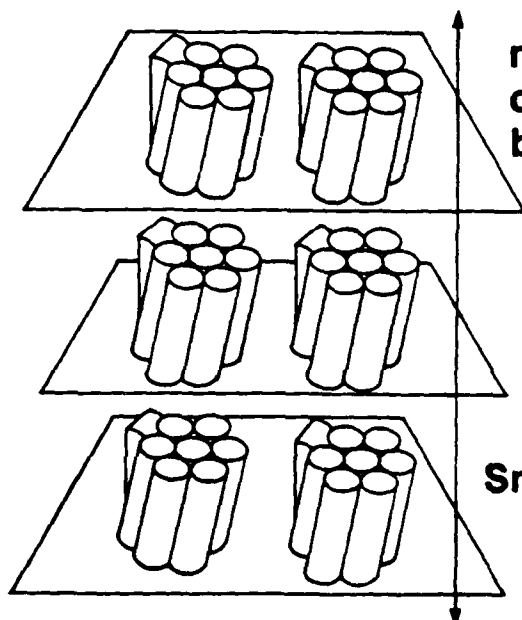


Smectic A



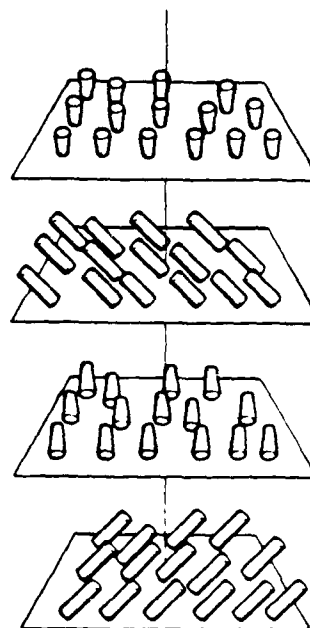
Smectic C

short-range
hexagonal order



no long-range
correlations
between layers

Smectics I and F



Chiral Smectic C

Origin of Ferroelectric Effects in Chiral Smectic Liquid Crystals

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Ferroelectric Materials: defined as materials that over a certain temperature range possess a spontaneous polarization (or net dipole moment per unit volume), which is reversible by an external electric field

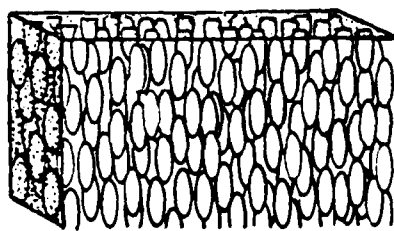
Dipolar ordering can arise in any system having a layered structure, tilt, and chirality of its constituent molecules
(R. B. Meyer, Harvard University, 1975)

Chiral smectic liquid crystals fulfill these requirements.

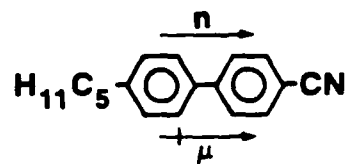
G1927

Diagram 1

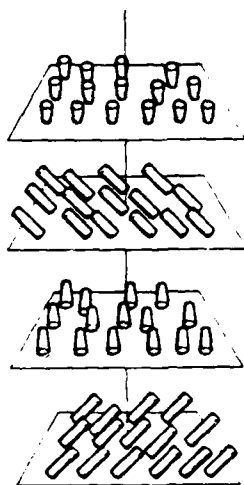
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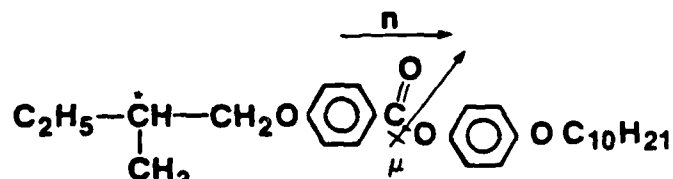
(a)



(b)



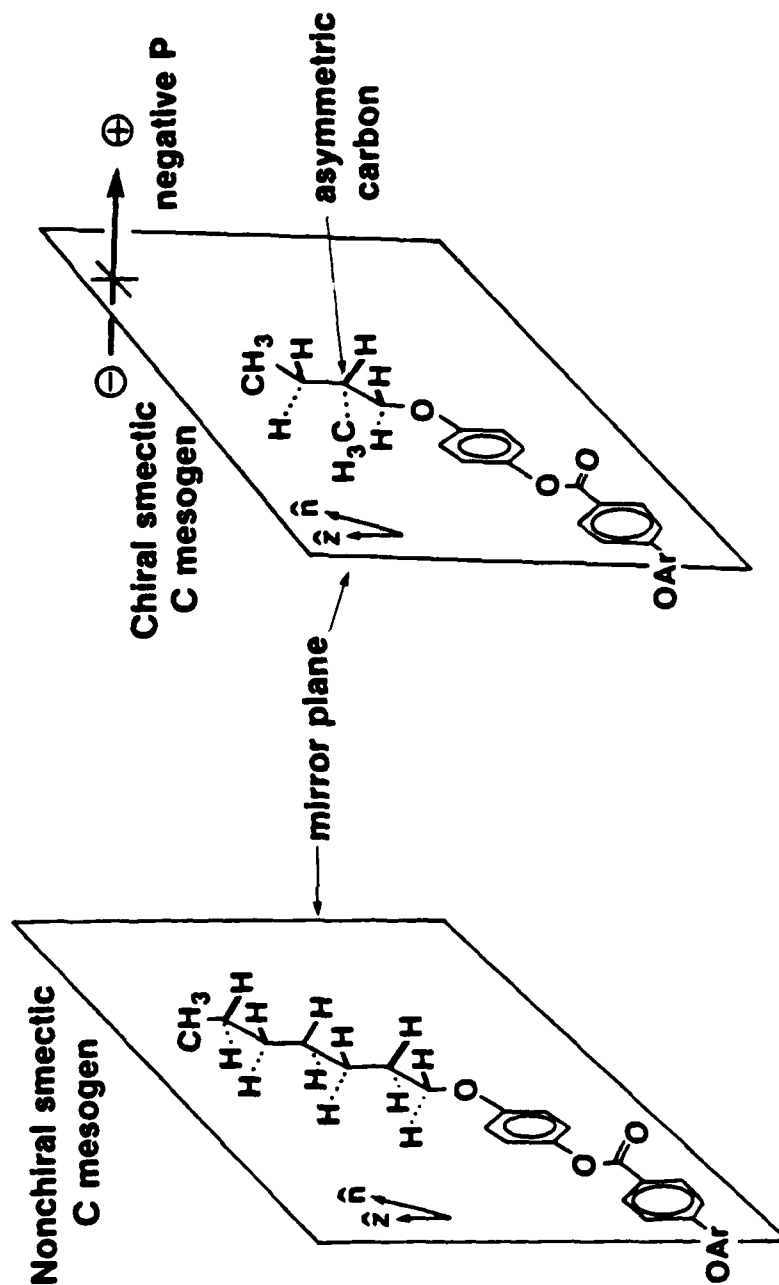
(c)



(d)

Chiral Centers Cause Spontaneous Formation of Permanent Dipoles by Reducing Molecular Symmetry

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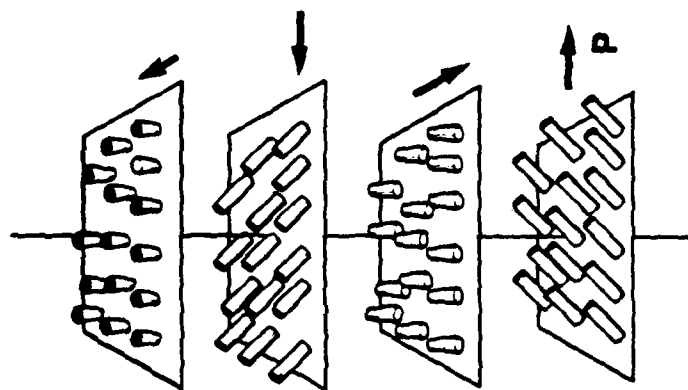


Walba et al., J. Am. Chem. Soc. 108, 5217 (1986).

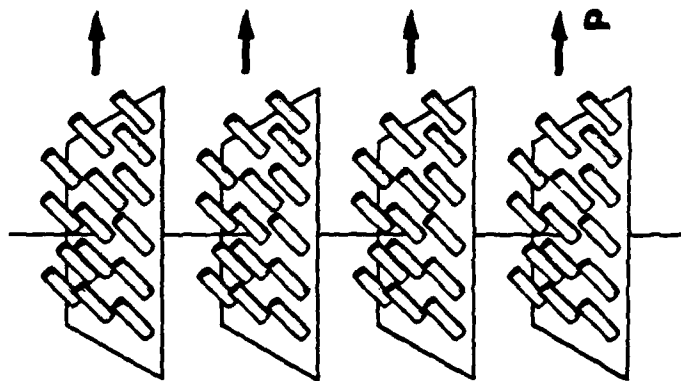
G1929

Chiral Smectic Liquid Crystals Must be Untwisted to Show Ferroelectric Properties

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(a) twisted structure
net average dipole moment = 0
no bulk ferroelectric properties.



(b) untwisted structure
nonzero average dipole
ferroelectric properties exhibited.

Methods of Untwisting the Chiral Smectic Helix

UR
LLE

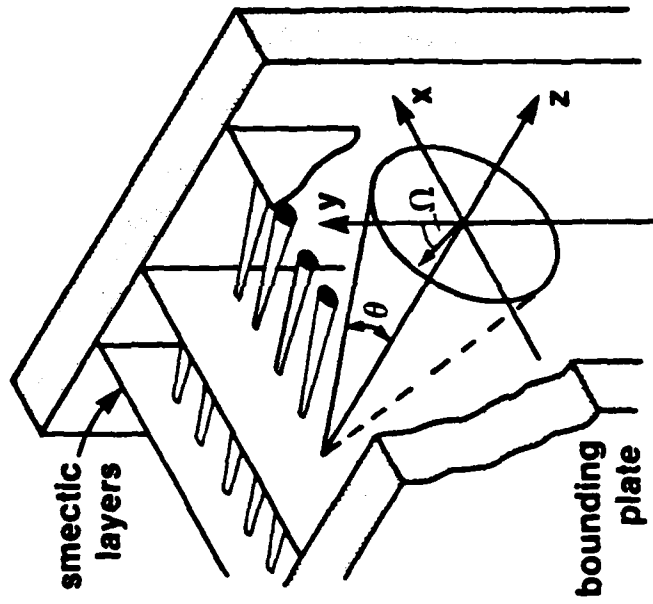


- Electric-field unwinding
- Magnetic-field unwinding
- Mixing of materials with opposite chirality
- Unwinding by surface forces and thin cell spacings

G1933

Elastic Unwinding of the Chiral Smectic C Helix by Surface Forces and Thin Cell Spacing

UR
LLE



θ = molecular tilt angle within layer

Ω = angle of tilt of molecule off surface (splay)

M. Handschy, N. Clark, and S. Lagerwall, *Phys. Rev. Lett.* **51**, 471-474 (1983).

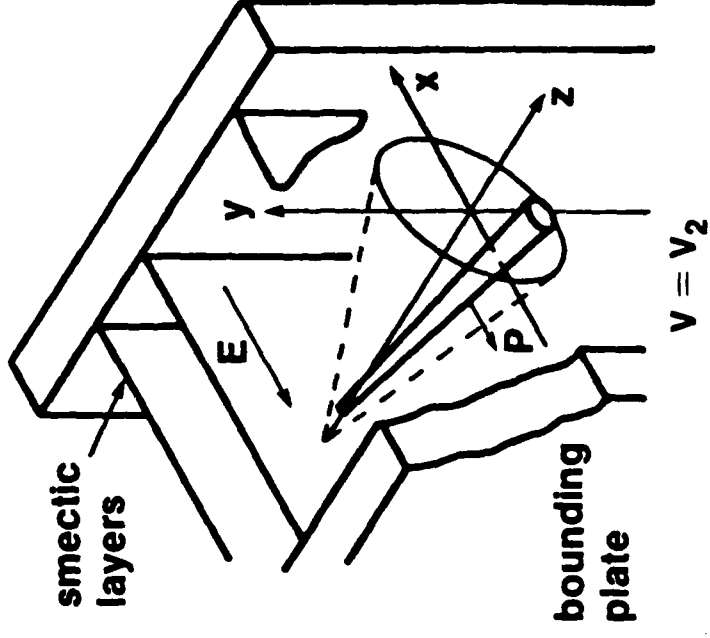
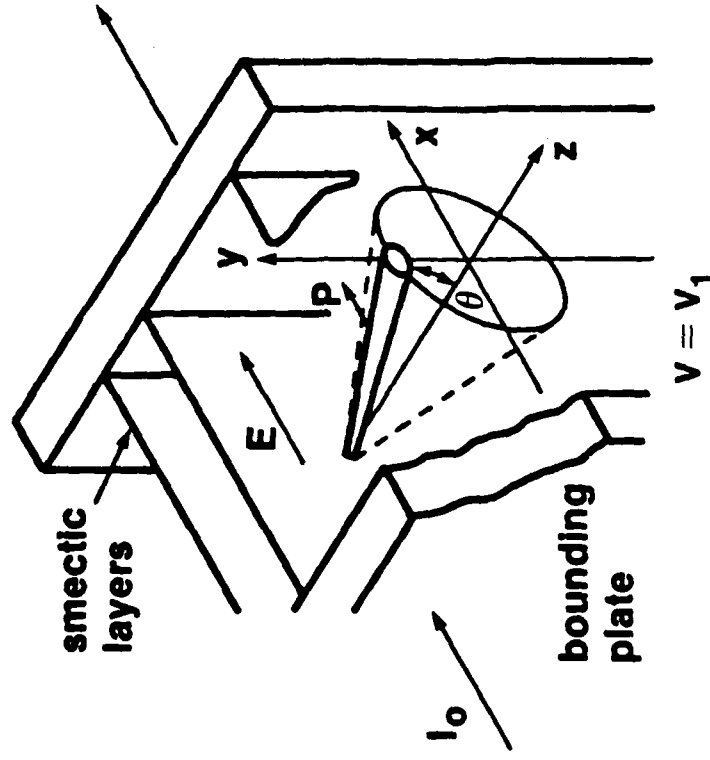
Surface-Stabilized, Ferroelectric, Liquid-Crystal Device (SSFLC)

UR
LLE

- Cell thickness $<$ pitch, bistable
- Most widely investigated
- Reasons:
 - fast response ($0.5 \mu\text{s}$ demonstrated)
 - bistability; controlled by boundary conditions
 - large electro-optic effect (20° - 60° rotation of an uniaxial material with $\Delta n \approx 0.2$)
 - slow development; lack of materials with room-temperature ferroelectric phases

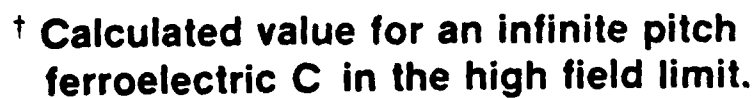
G1937

Director Reorientation in the SSFLC Device



- Angle of deflection = 2θ (θ = molecular tilt angle within smectic layer)
- Typical values for θ are between 22.5° and 45° (material dependent)

UR
LLE

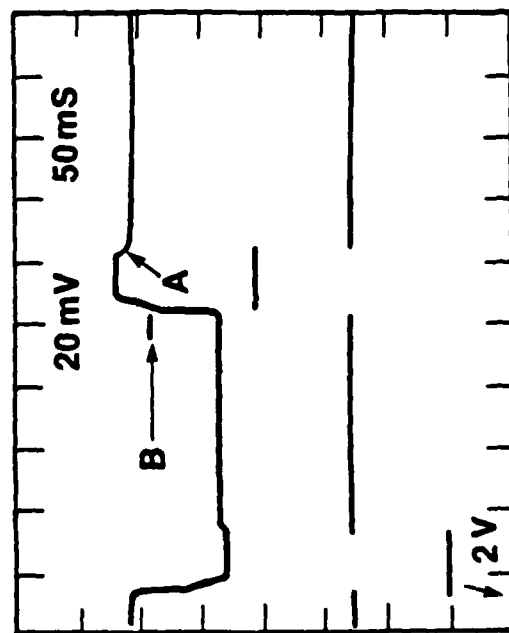


G1938

Bistable Switching in Thin Ferroelectric Liquid-Crystal Cell

UFR
LLE

cell spacing = 1-2 μm ; response time = 1 ms



A = field-off relaxation top trace = optical response
B = bulk-surface switching transition bottom trace = 3-V, 5-ms applied pulse

J. Patel, *Appl. Phys. Lett.* 47, 1278 (1985).

G1942

Materials Considerations

UR 
LLE

- Desirable properties
 - high chemical stability
 - radiation hardness
 - broad-range ferroelectric phase (room temperature)
 - large spontaneous polarization (low operating voltage)
 - long intrinsic helical pitch ($> 5 \mu\text{m}$) (fast response)
 - smectic A - chiral smectic C phase transition
- Bulk of investigations employed DOBAMBC and HOBACPC
 - easy synthesis
 - large spontaneous polarization
 - not suitable for room-temperature devices

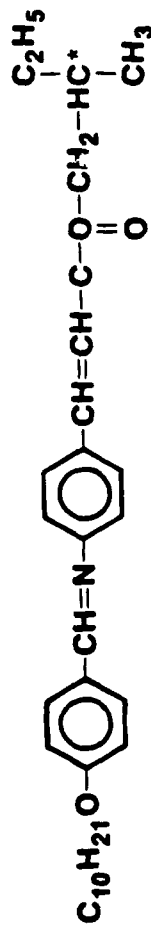
G1946

Chiral Smectic C Mesogens

UR
LLE

S_c Range

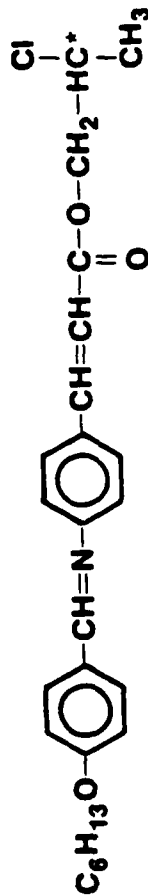
Structure



DOBAMBC

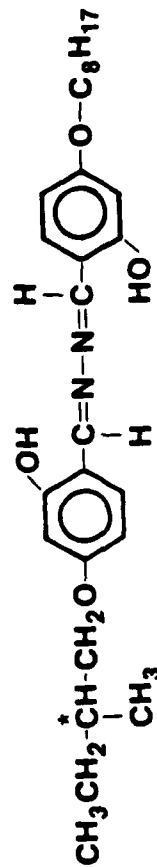
85-90°C

62-74°C



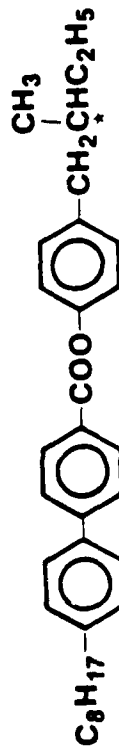
HOBACPC

100-134°C



disubstituted benzalazine

70.3-87°C



CE-8

Recent Materials Advances



- Eutectic mixtures of existing chiral smectic C materials
- Nonchiral smectic C mixtures doped with chiral smectic C additives
- New, more stable chiral smectic C mesogens with ferroelectric phases near room temperature
- Commercial availability of room-temperature chiral smectic C mixtures (June 1986)

G1948

SURVEY OF COMMERCIALY AVAILABLE CHIRAL SMECTIC C MESOGENS

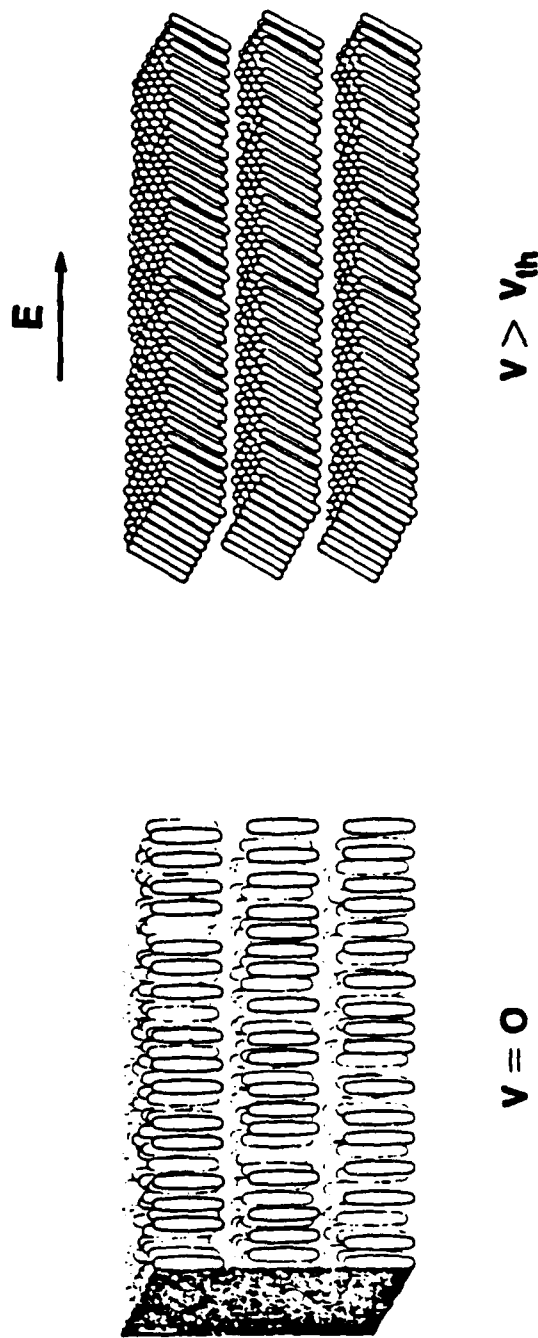


Vendor	Catalog #	Single substance (S) or mixture (M)	Chiral S _c * Range (°C)	Tilt Angle (θ) at 20°C, Degrees	Δn @ 589 nm, 25°C
E. Merck	ZLI-3488	M	-30 to +61	25.5	--
"	ZLI-3489	M	-30 to +65	29.0	--
"	ZLI-3654	M	-30 to +62	25.0	--
"	ZLI-3774	M	-30 to +62	25.5	--
"	ZLI-3775	M	-30 to +61	26.0	--
"	ZLI-4003	M	-20 to +62	23.0	--
BDH	SCE-3	M	0 to +74	25.0	0.17
"	SCE-4	M	0 to +57	23.0	0.17
"	SCE-5	M	-15 to +63	22.5	0.18
"	SCE-6	M	-15 to +63	23.5	0.18
Displaytech	W7	S	+9 to +27	23.0	0.105
"	W81	S	+15 to +56.5	23.0	0.105
"	W37	S	+25 to +37.5	23.0†	0.105
"	W82	S	+30.5 to +70.5	23.0†	0.105
"	W46	S	+64 to +80	23.0†	0.105
"	MDW7	S	+25 to +45.8	23.0†	0.105

† Values estimated from mixture data.

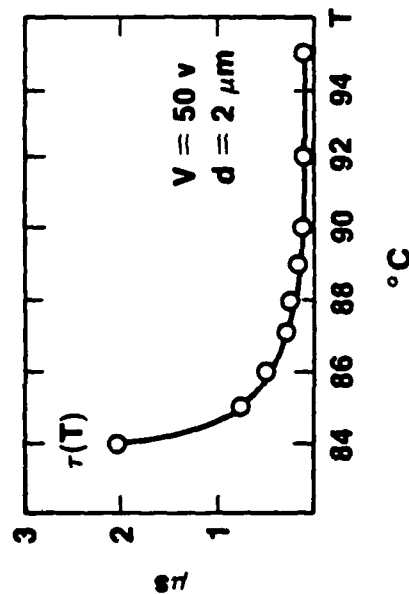
Electroclinic Effect UR LLE

- Garoff and Meyer — 1978(4)
- Coordinated tilt of molecules within layer under influence of an electric field.
- Occurs in smectic A materials containing chiral centers-hindered rotation.
- Response time $\ll$ Fredericks transition in nematics.

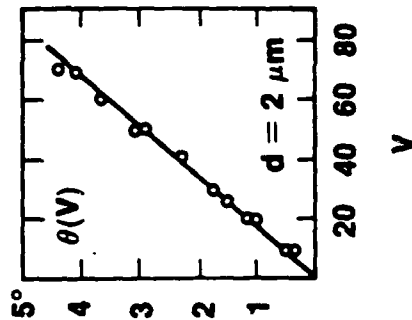


4. S. Garoff and R. B. Meyer, "Electroclinic Effect at the A-C Phase Change in a Chiral Smectic Liquid Crystal," *Phys. Rev. A* **19**, 338 (1979).

Electroclinic ("Soft Mode") Effect - Optical Response



Critical slowing down of switching speed on approaching the A'-C' transition. The material is DOBA-1-MPC, in the A' phase (83°C to 102°C).



Linearity in the tilt angle response versus applied voltage in DOBA-1-MPC at 86°C .

- Achievable response: $< 100\text{ ns}$ with high-temperature compounds
 $< 1\text{ }\mu\text{s}$ at room temperature
- Approximately 10-100 times faster than SSFLC mode

S. T. Lagerwall et al., *Mol. Cryst. Liq. Cryst.* **152**, 503-587 (1987).

CENTER FOR NIGHT VISION AND ELECTRO-OPTICS
HISTORICAL PERSPECTIVE: LIQUID CRYSTAL RESEARCH AT FORT BELVOIR

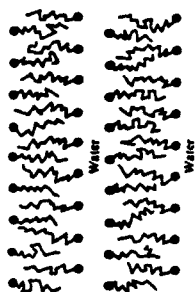
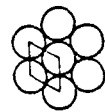
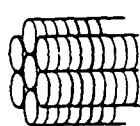
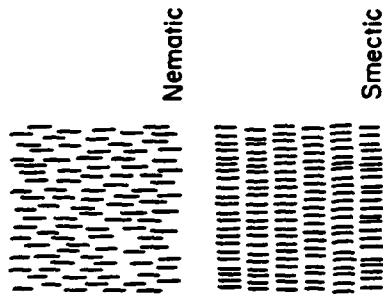


Fig. 1.1.4. The lamellar or neat phase of soaps.

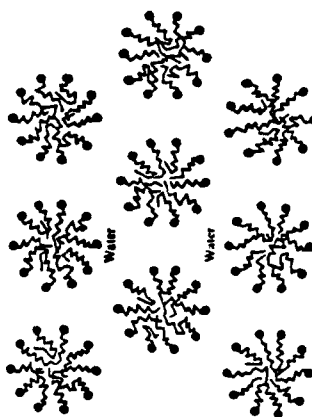


Fig. 1.1.5. The hexagonal or middle phase of soaps.

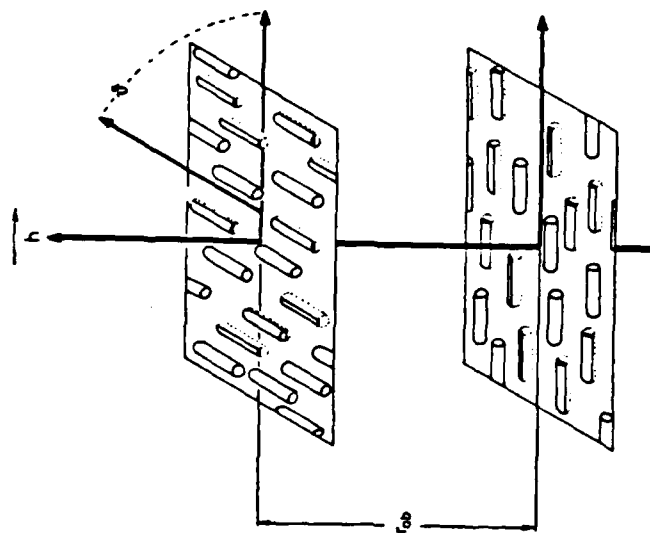


Fig. 21. Schematic representation of the cholesteric phase: θ = twist angle, $r_{\perp}$ = distance of molecules perpendicular to the director, h = pitch axis

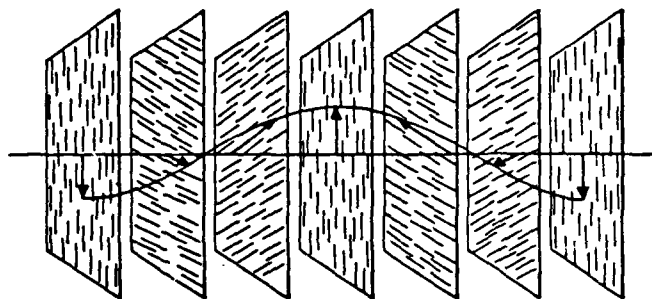
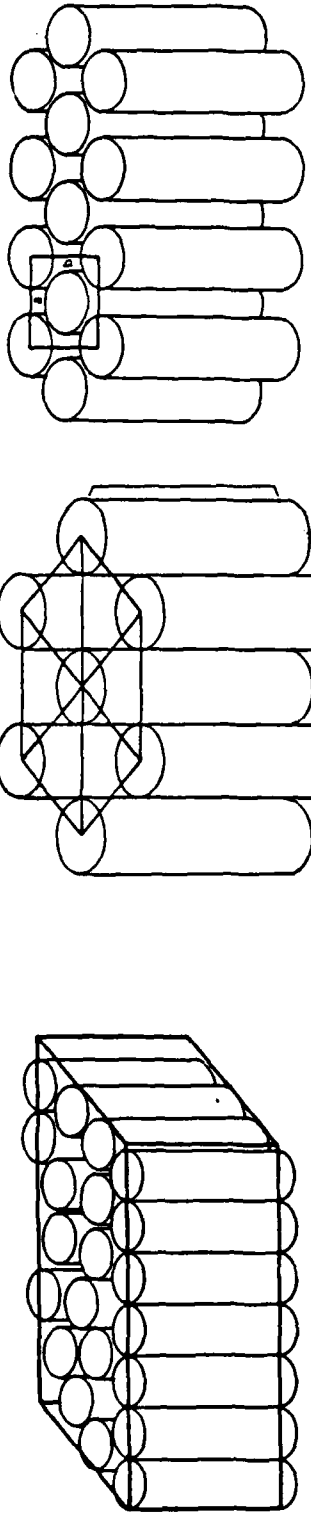
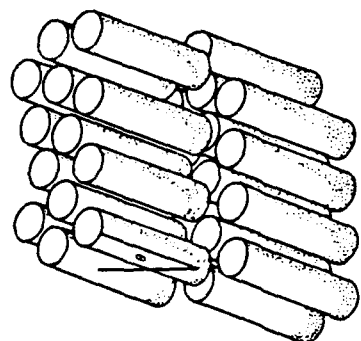


Fig. 1.1.2. The cholesteric liquid crystal: schematic representation of the helical structure.



Disordered arrangement of molecular centres in a smectic A phase.

The packing arrangement of molecules in a layer in the smectic E phase (b-e)—see also Fig. 5.1



Structure of the smectic C phase: there is no regular arrangement of the molecular centres in the planes of the unstructured layers. Tilt angles (θ) may range upwards from $\leq 10^\circ$.

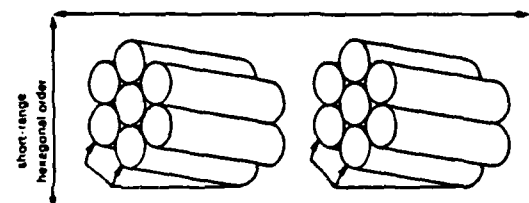
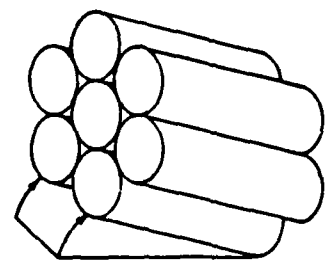


Figure 6.1 Structure of the S_G phase.



Hexagonal close-packed molecules in the smectic G phase

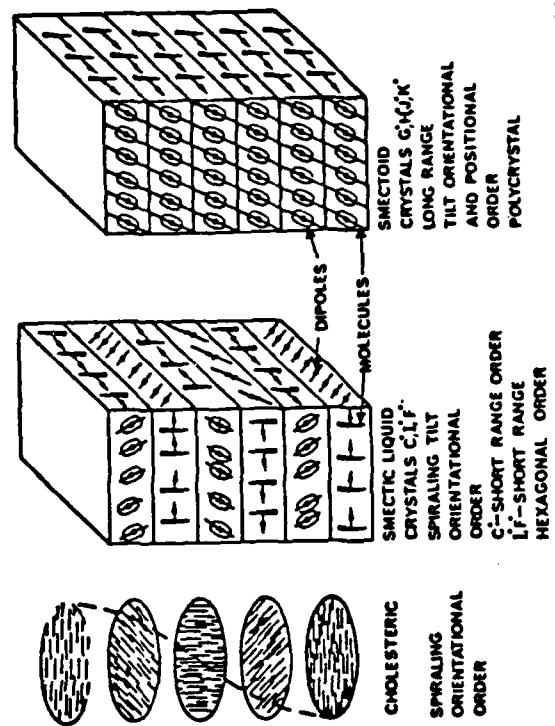


Figure 1. The structures of the cholesteric, ferroelectric smectic liquid crystal, and ferroelectric crystal (smectoid) phases.

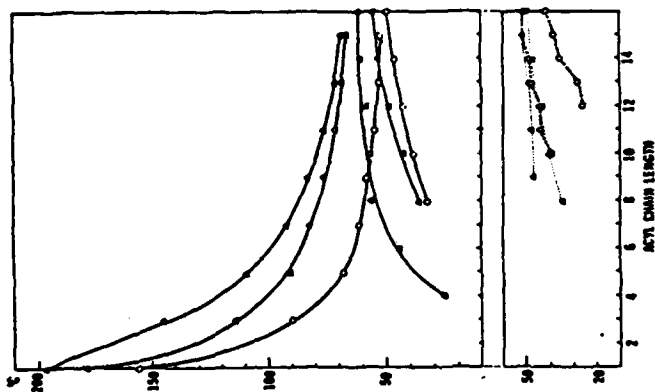


Fig. 18. Transition temperatures of ω -phenylalkanoates. Transitions as defined in Fig. 17. Δ , Cholesteryl ω -phenylalkanoates, III; $\circ$, 5 α -cholesteryl ω -phenylalkanoates, IV; $\square$, 5 α -cholestan-3 β -yl ω -phenylalkanoates, XV.

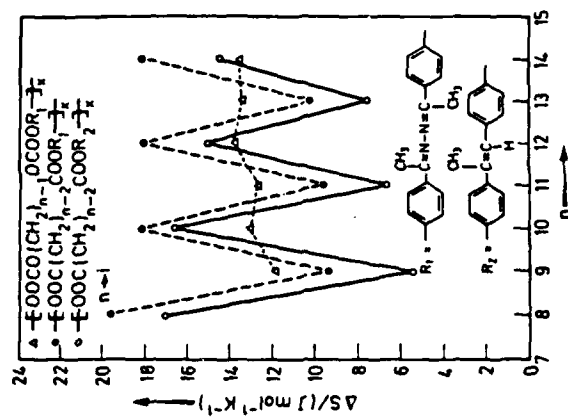


Fig. 17. Transition temperatures of alkanones. Solid lines: cholesteric-isotropic phase transitions; broken lines: smectic-cholesteric phase transitions. Δ , Cholesteryl alkanones, I; Δ , 5-cholesteryl alkanones, II; $\circ$, 5 α -cholestan-3 β -yl alkanones, XIV; $\bullet$, 5 α -cholestan-3 β -yl alkanones, 75.

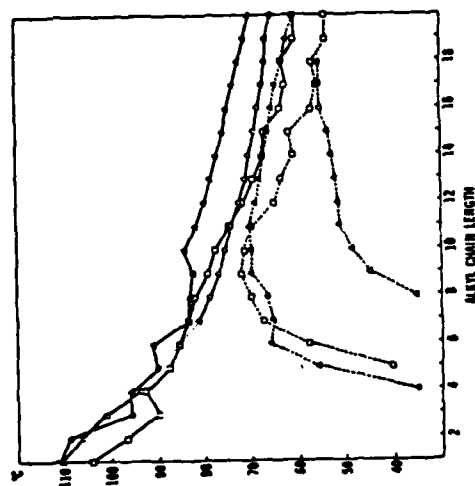
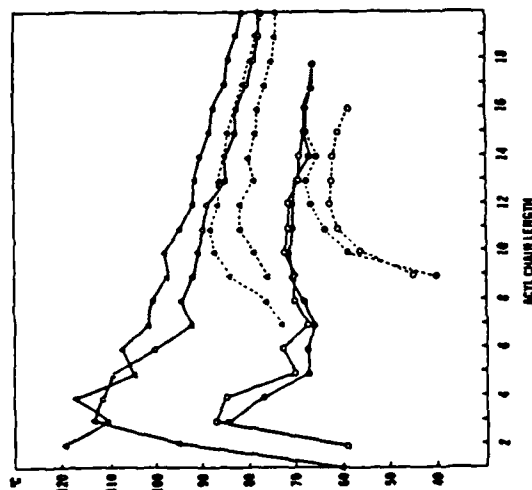


Fig. 19. Transition temperatures of carbonates. Transitions as defined in Fig. 17. Δ , Cholesteryl alkyl carbonates, V; $\square$, cholesteryl S-alkyl thiocarbonates, VI; $\circ$, 5-cholesteryl alkyl thiocarbonates, VII.



TEMPERATURE INTERVALS OF VISIBLE SPECTRUM OF SELECTIVE REFLECTION^a

n	I	II	III	IV	V	VI	VII	XIV	XV	XVI	XVII
5	—	—	—	—	—	—	56.3–56.0	—	—	—	—
6	—	—	—	—	—	56.0–53.0	68.5–68.0	—	—	—	—
7	—	72.7–71.5	83.0–82.0	—	—	68.0–67.0	64.3–64.1	—	—	—	34.3–31.3
8	—	74.0–72.9	—	—	41.0–37.3	—	67.3–66.7	—	—	—	47.8–47.0
9	77.9–76.5	—	—	50.3–48.1	50.0–45.5	—	—	—	—	—	52.4–51.9
10	77.1–76.1	—	39.5–39.3	—	51.0–49.4	—	70.2–70.1	—	—	—	55.4–55.2
11	—	—	47.0–44.2	49.9–48.7	52.3–51.5	—	70.5	61.9–61.1	—	39.5–39.2	—
12	—	—	44.6–44.3	—	53.0–52.1	—	70.5	63.6–63.1	26.6–26.1	43.5–42.1	—
13	—	—	50.0–48.1	51.1–49.8	53.1–52.5	—	68.7	—	—	43.6–42.6	—
14	—	—	48.7–48.3	47.35	53.9–52.9	—	67.8	—	36.0–35.6	—	—
15	—	—	53.0–52.0	52.4–51.6	54.9–54.1	—	66.5	—	—	41.4–40.3	—
16	—	—	51.7–51.3	49.6–49.4	55.7–55.0	—	65.4	—	44.0–41.7	—	—
17	—	—	—	—	56.2–55.6	—	64.5	—	—	—	—
18	—	—	—	—	56.4–55.8	57.8–57.4	63.2–63.1	—	—	—	—
19	—	—	—	—	55.1–49.9	—	62.5–62.3	—	—	—	—
20	—	—	—	—	—	57.0–56.0	60.6–60.4	—	—	—	—

^a The temperature values were obtained by optical microscopy. n = alkyl or acyl chain length, respectively; for structures see Table II. I, cholesteryl alkanates; II, *S*-cholesteryl alkanethioates; III, cholesteryl ω -phenylalkanoates; IV, *S*-cholesteryl ω -phenylalkanethioates; V, cholesteryl alkyl carbonates; VI, cholesteryl *S*-alkyl thiocarbonates; VII, *S*-cholesteryl alkyl thiocarbonates; XIV, 5 α -cholestan-3 β -yl alkanates; XV, 5 α -cholestan-3 β -yl ω -phenylalkanoates; XVI, 5 α -cholestan-3 β -yl alkyl carbonates; XVII, 5 α -cholestan-3 β -yl *S*-alkyl thiocarbonates.

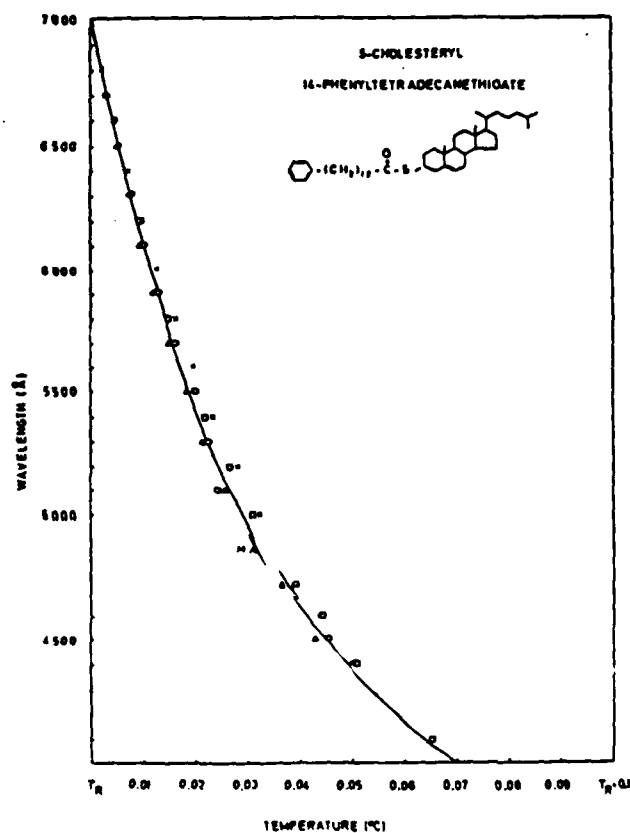


Fig. 23. Wavelength of maximum selective reflection as a function of temperature. Material: *S*-cholesteryl 14-phenyltetradecanethioate. x, Data set I; L, data set II, measured on same day on same sample as set I; Δ, data set III, second sample, cooled at 2 m²/min, measured 8 days after set I; O, data set IV, third sample, cooled at 5 m²/min, measured 9 days after set I (cf. Table IX). [Reproduced from Linnul et al., *Mol. Cryst. Liquid Cryst.* 26, 245 (1974), with permission.]

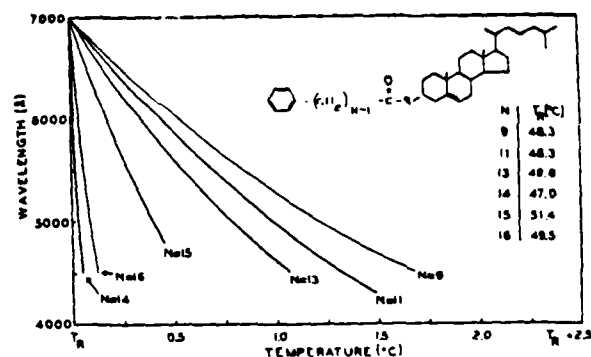


Fig. 24. Wavelength of maximum selective reflection as a function of temperature. Materials: *S*-cholesteryl ω -phenylalkanoates.

	AMPHIPHILIC	NON AMPHIPHILIC	
MONOMER UNIT		CYLINDRIC DISCOTIC	
MAIN CHAIN POLYMER			
SIDE CHAIN POLYMER			

Fig. 1. Classification of liquid crystalline monomers and polymers

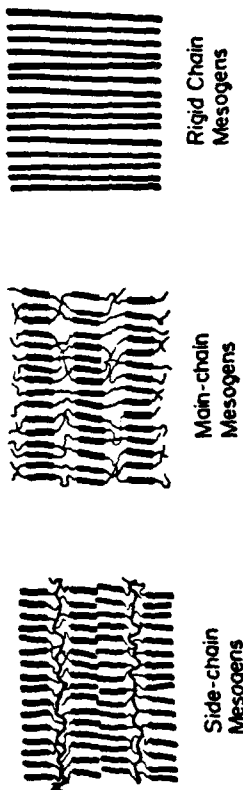


Fig. 13. Schematic representation of macromolecular liquid crystals. A smectic structure is assumed for all cases

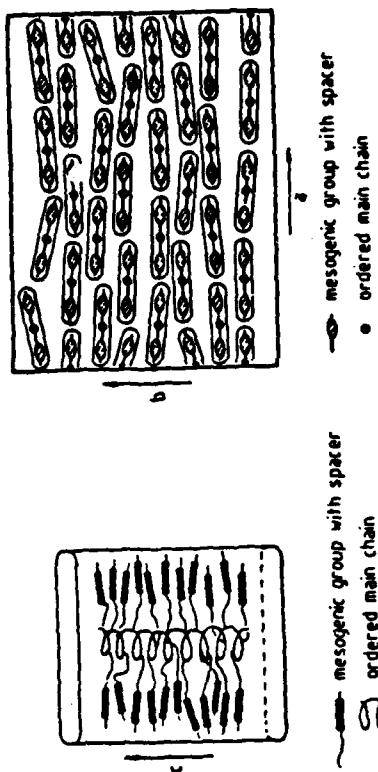


Fig. 31. Schematic model of the smectic structure of these liquid crystalline side chain polymers

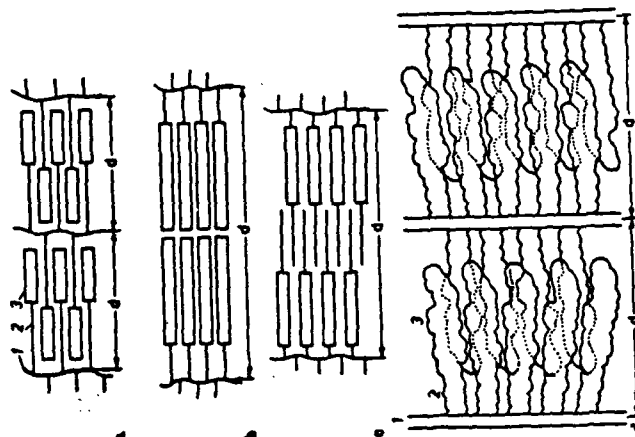


Fig. 10-4. Schematic of side chain packing of macromolecules in S_c mesophase of oriented LC polymers. (a) one-layer packing; (b) two-layer packing; (c) packing with partial overlapping of mesogenic fragments (side chains are designated by "dots"); (d) packing with partial overlapping of mesogenic fragments (side chains are designated by "dots"). (Side groups of neighbouring macromolecules (in the cases a, c and d) are arranged in different planes parallel to the plane of the figure)

**CENTER FOR NIGHT VISION AND ELECTRO-OPTICS
CURRENT LIQUID CRYSTAL RESEARCH SPONSORED BY NVEOC**

Liquid Crystals in R&D Tasks



solicited by Naval Air Development Center under RFP N62269-87-R-0218

Tri-Service Contracts awarded to be awarded

- The University of Rochester
Institute of Optics / Laboratory for Laser Energetics
K. L. Marshall, S. D. Jacobs, and coworkers
- Optical Shields, Ltd.
J. L. Fergason and coworkers
- Hughes Research Laboratories
S. T. Wu and coworkers
- Honeywell
Physical Sciences Center
S. Jenekhe and coworkers

Liquid Crystals in R&D Tasks



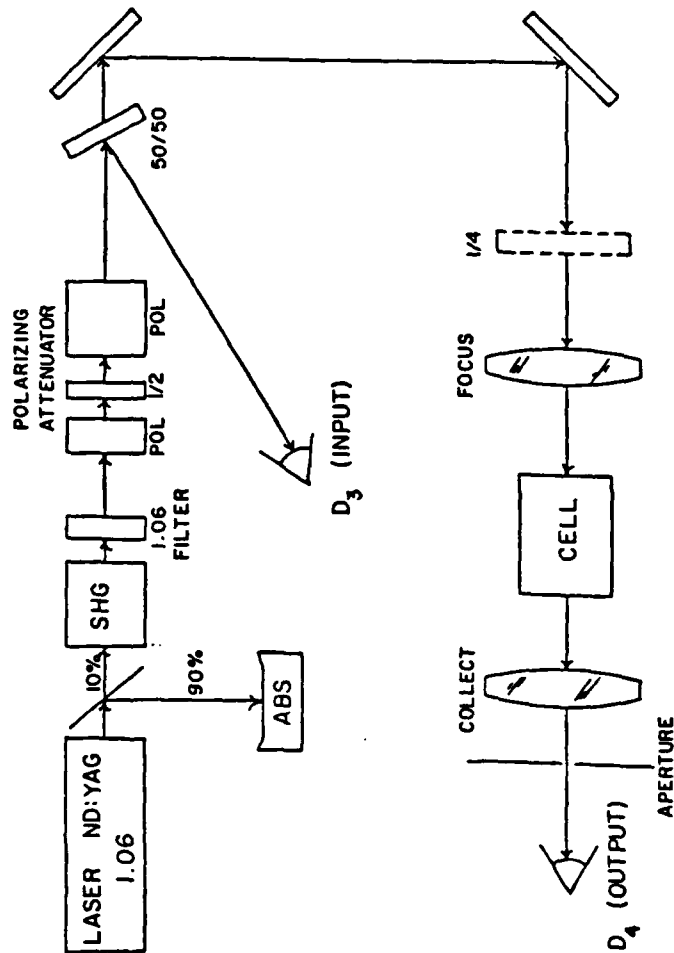
to be awarded under BAA Issued by DARPA / Army / CNVEO

- Kent State University
Liquid Crystal Institute
M. A. Lee, J. W. Doane, and coworkers
- The Pennsylvania State University
College of Engineering
I. C. Khoo
- Optical Shields, Ltd.
J. L. Fergason and coworkers
- Honeywell
Systems and Research Center
S. K. Lo and coworkers

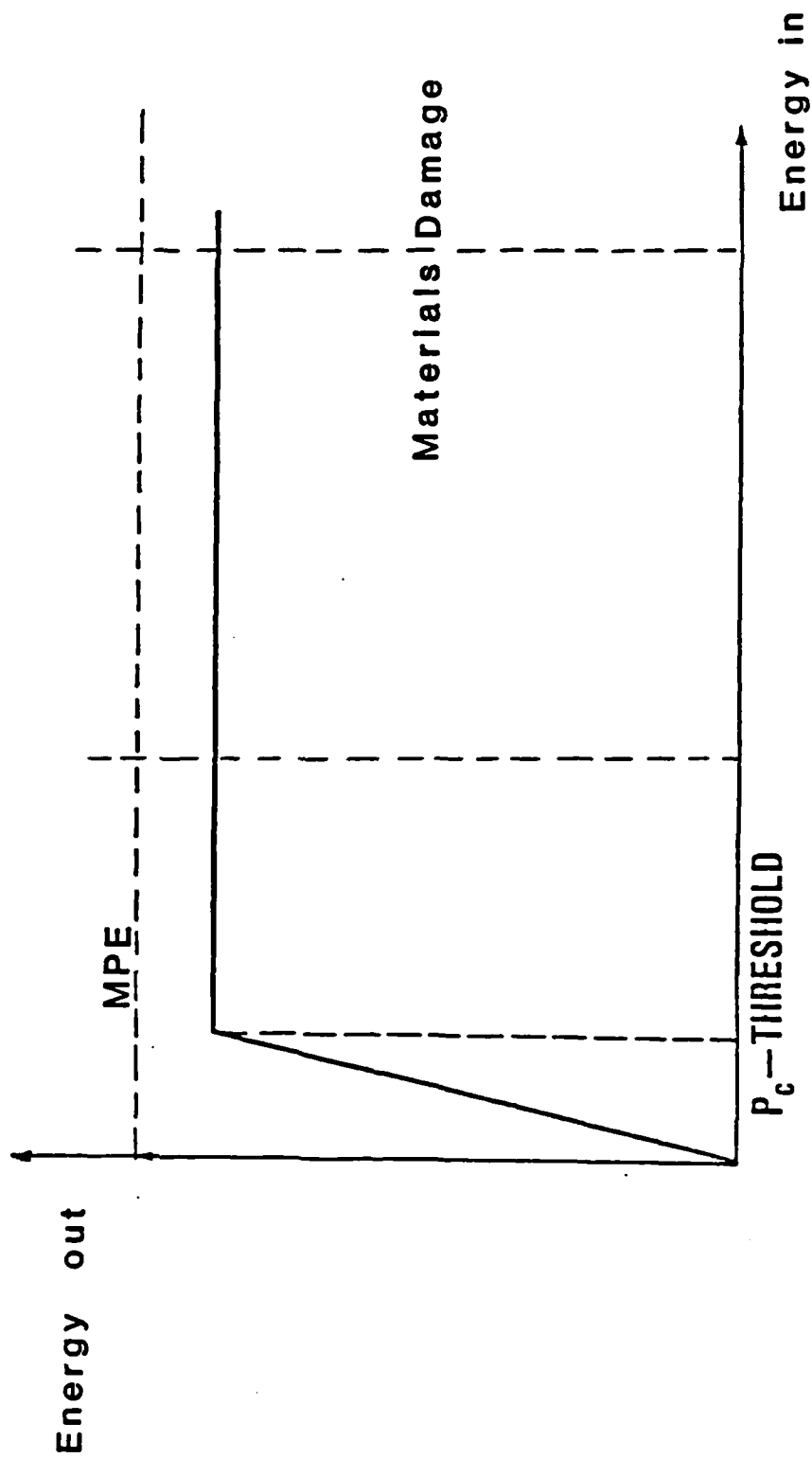


Nonlinear Measurements

- The University of Central Florida
Center for Research in Electro-Optics and Lasers
M. J. Soileau, E. W. Van Stryland, and coworkers

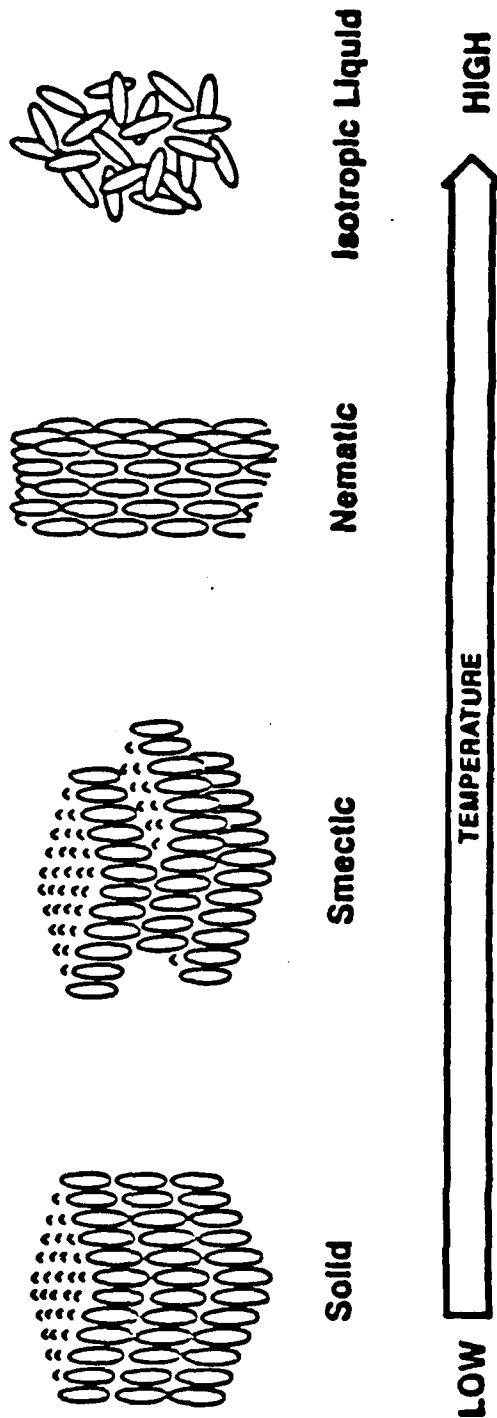


Power/Energy Limiter, ideal



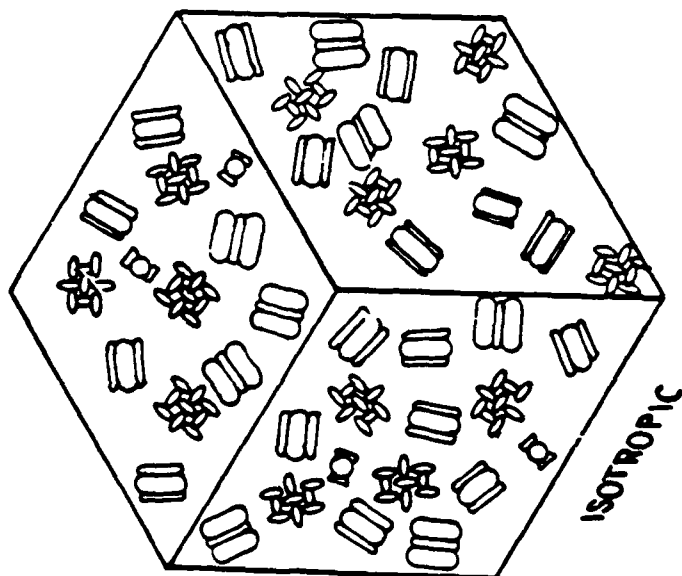
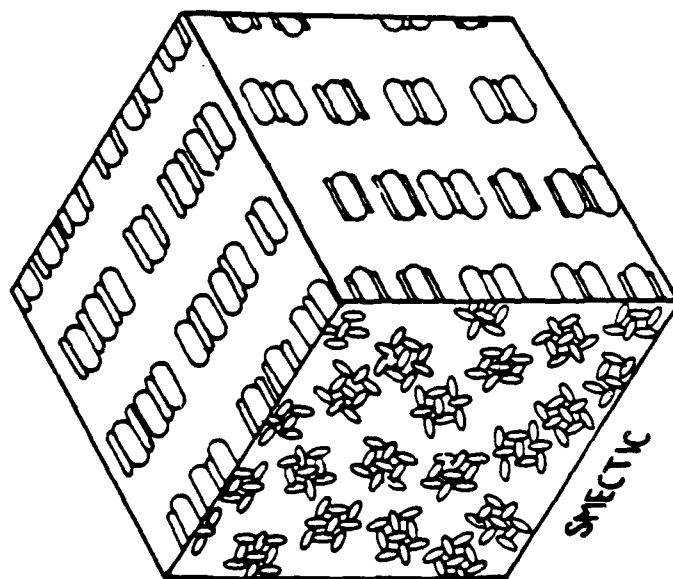
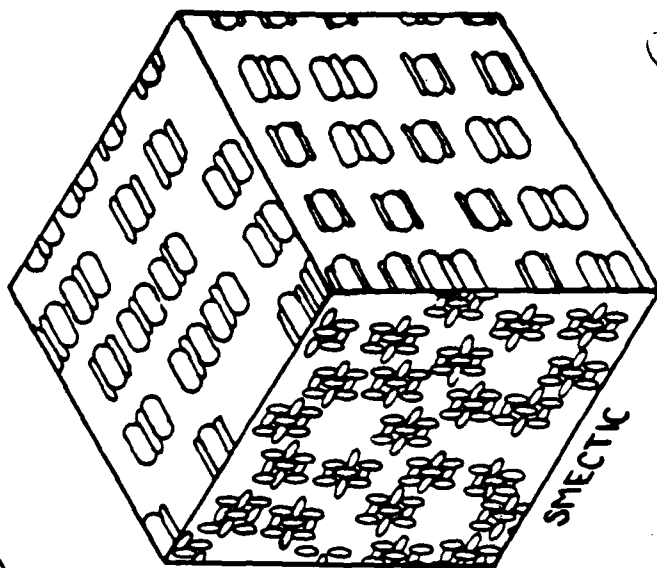
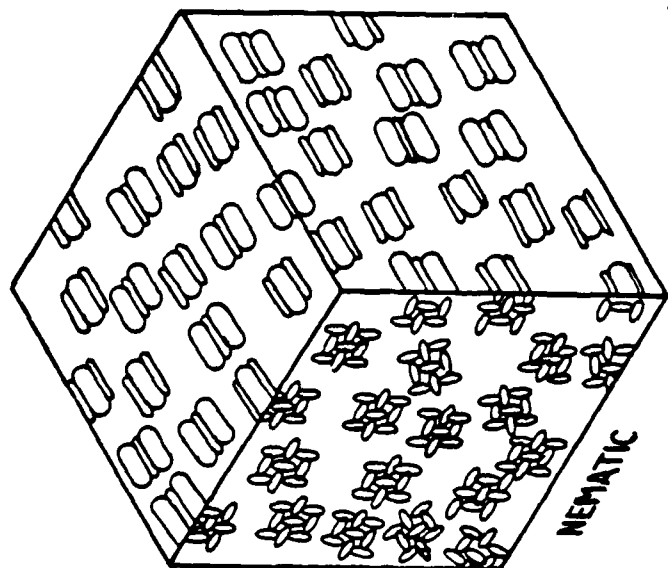
PHASES OF MATERIAL

Liquid Crystal Phase

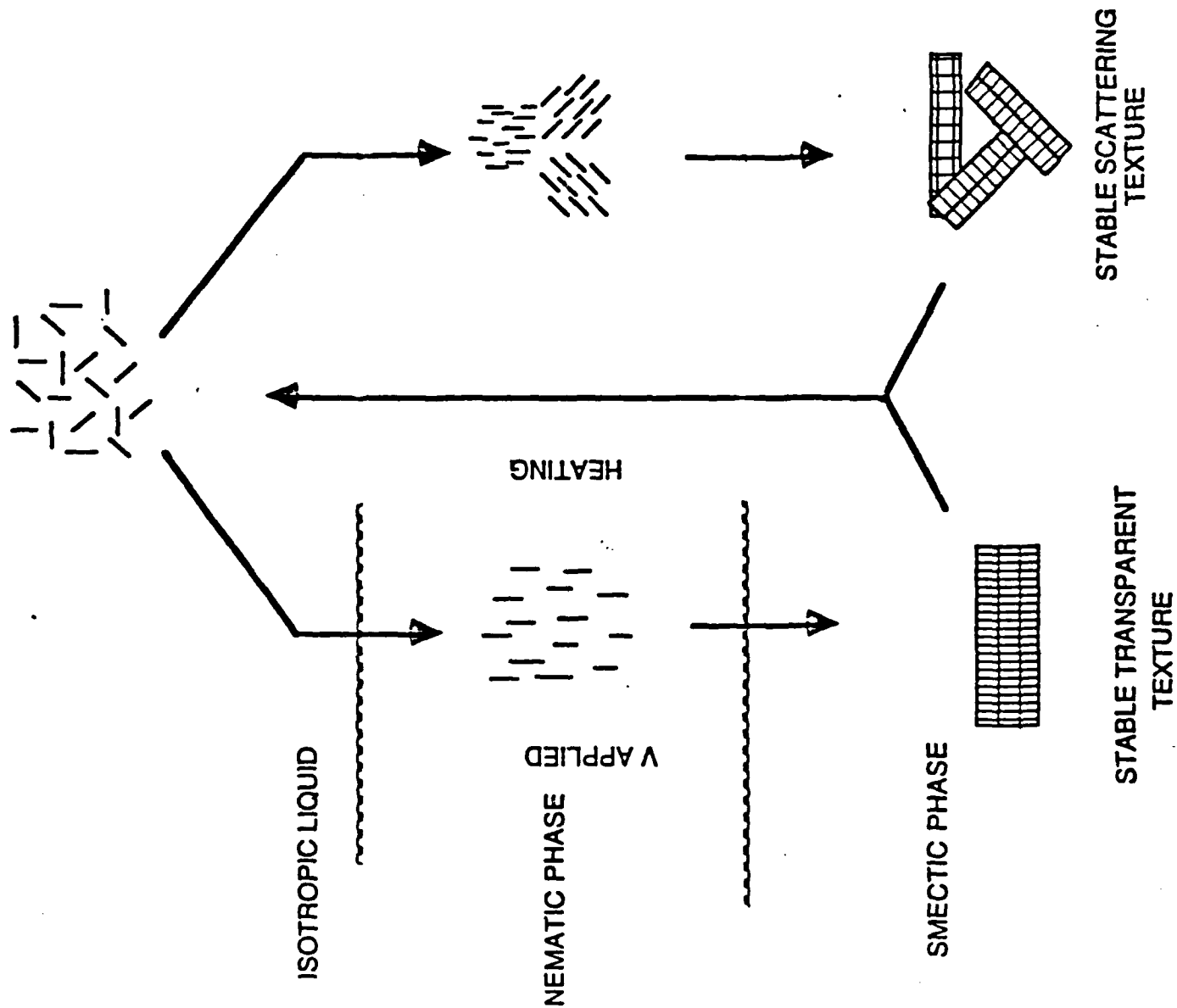


NEMATIC: Orientation Order

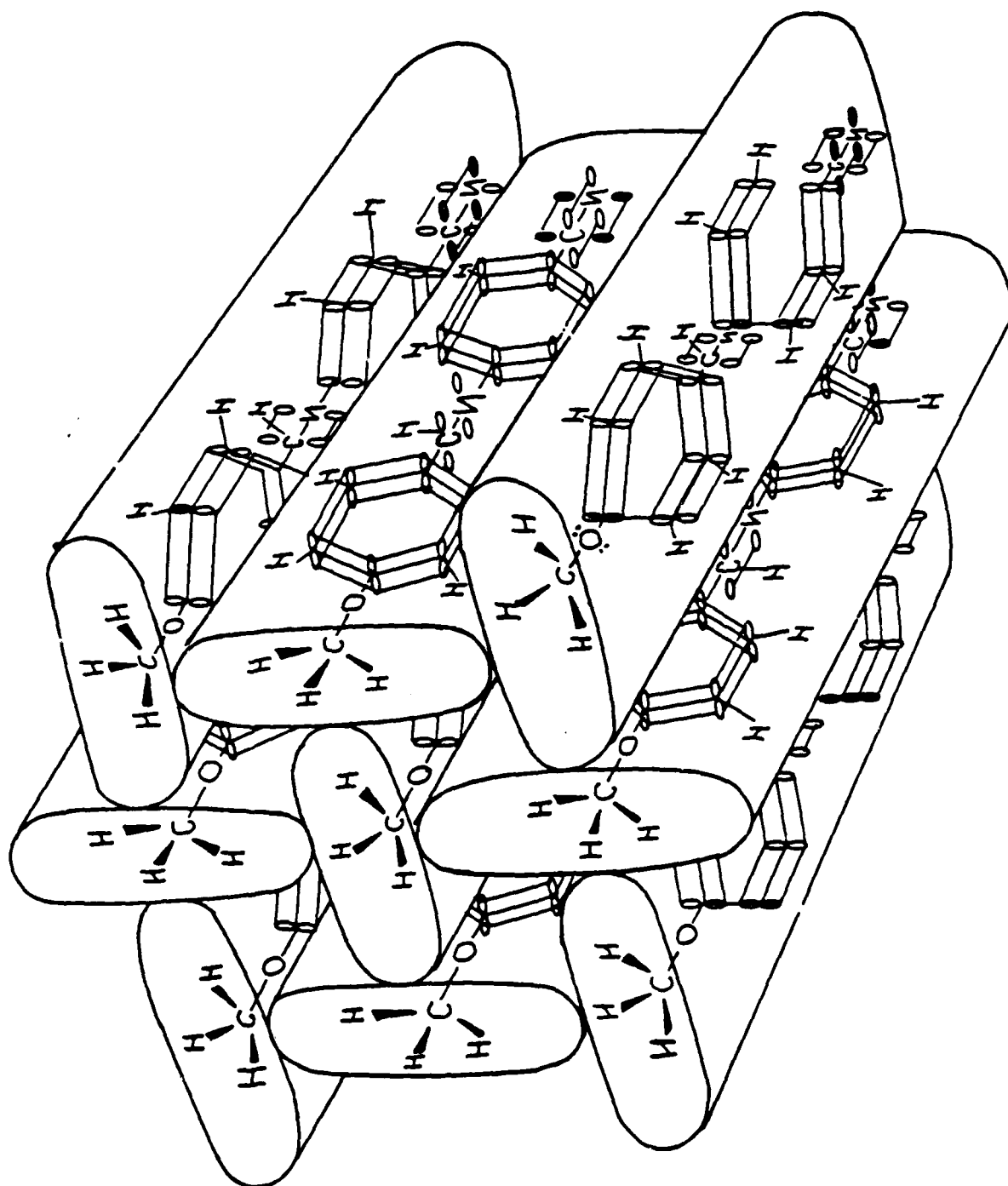
SMECTIC: Orientation & Layer Order



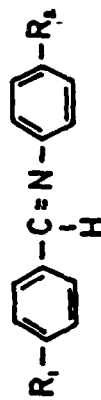
6.



65



Nonlinear Studies of Schiff Bases



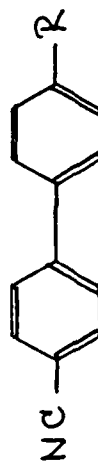
Sample	Color	R ₁	R ₂	P _c (kW)		n _d × 10 ¹⁴ (esu)	
				at 532 nm	at 1064 nm	at 532 nm	at 1064 nm
MEBBA	Orange	CH ₃	C ₆ H ₅	7 ± 1	.55 ± .05	6 ± 1	
ETBBA	Light Yellow	C ₂ H ₅	C ₆ H ₅	8 ± 1	.5 ± .05	17 ± 2	
IPBBA	Light Yellow	C ₂ H ₅	C ₆ H ₅	8 ± 1	.5 ± .05	13 ± 2	
BBIPA	Orange	C ₆ H ₅	C ₆ H ₅	7 ± 1	.5 ± .05	12 ± 2	
PEBBA	Orange	C ₆ H ₁₁	C ₆ H ₅	7 ± 1	.55 ± .05	14 ± 2	
CS ₂	Clear			8 ± 1	Small	130	

Mol. Cryst. Liq. Cryst. 127, 321 (1985)

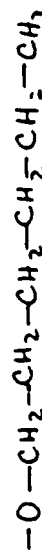
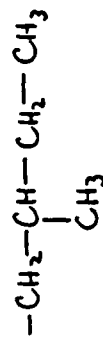
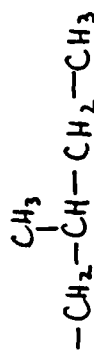
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CYANO BIPHENYL DERIVATIVES

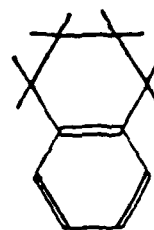
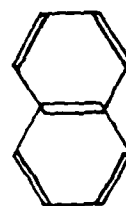
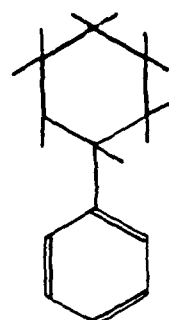
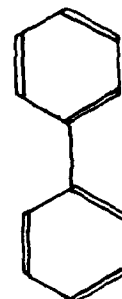
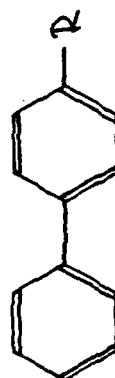
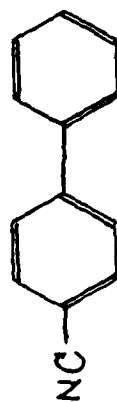
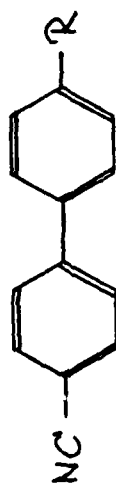


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PRECURSORS AND ANALOGUES



CENTER FOR NIGHT VISION AND ELECTRO-OPTICS
LIQUID CRYSTAL ELECTRO-OPTIC SHUTTER

LIQUID CRYSTAL E-O SHUTTER

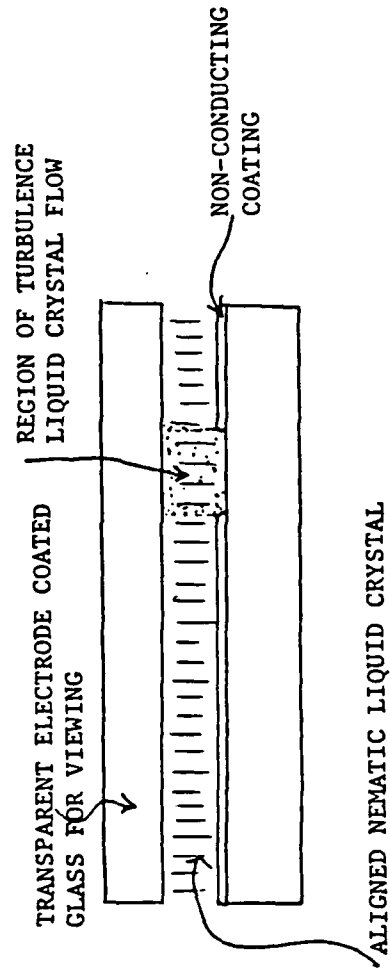
- BACKGROUND
 - NEED FOR CHOPPER
 - PRESENT SOLUTIONS
 - METAL TOOTH WHEEL: ON/OFF
 - GERMANIUM SPIRAL: FOCUS/DEFOCUS
 - DISADVANTAGES
- PROPOSED SOLUTION
 - LINE SCAN CHOPPER
 - DESIRED FEATURES
 - PRINCIPLE OF OPERATION
 - PROGRESS: DR I. C. KOO, PENN. STATE
- CONCLUSIONS
 - PROBLEMS
 - APPROACHES

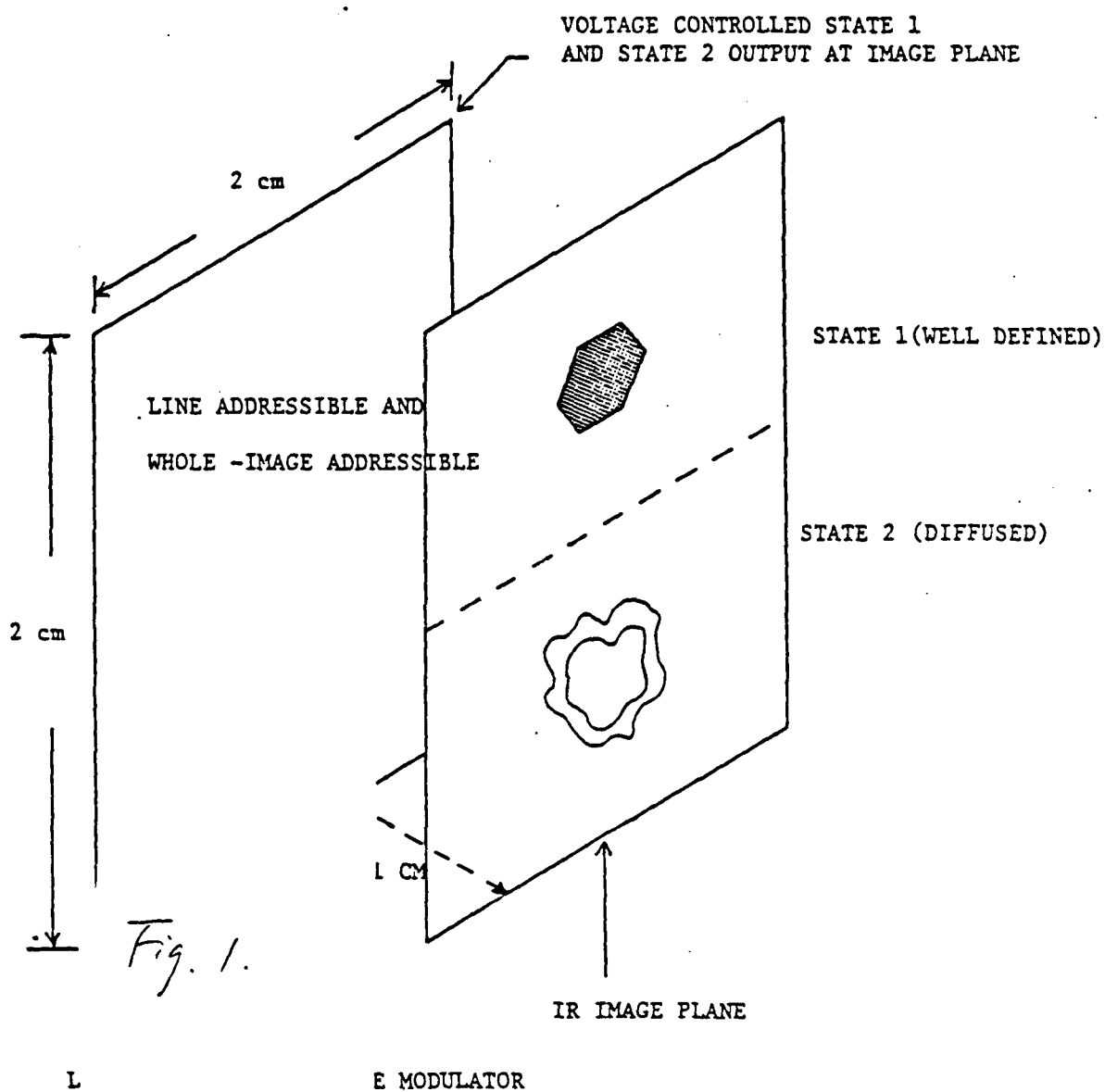
LINE SCAN CHOPPER-DESIRED FEATURES

- OPERATES BY FORWARD SCATTERING, NOT TRANSMISSION REDUCTION
- WIDE ACCEPTANCE ANGLE: 40° FULL ANGLE
- ELECTRICALLY LINE ADDRESSABLE
- LARGE ARRAY SIZE: 0.5" SQUARE
- LINE WIDTH: <100 MICRON
- LOW INSERTION LOSS: <20%
- BROADBAND OPERATION: 8-12 MICRON
- SWITCHING TIME: <1 ms, ON AND OFF
- FORWARD SCATTERING: >95% INTO ANNULUS 10 LINES DIAMETER
- OPERATING TEMPERATURE: -20°C TO +50°C

PRINCIPLE OF OPERATION

- DYNAMIC SCATTERING IN NEMATIC LIQUID CRYSTAL
- APPLIED E FIELD INDUCES TURBULENT MOTION
- MOTION CAUSES OPTICAL SCATTERING





LIQUID CRYSTAL CANDIDATES

- **NEGATIVE ANISOTROPIC DIELECTRIC NEMATICS**

- E-7, ZLI-1132, NP-5: HIGH Δn , POSITIVE $\Delta \epsilon$
- ZLI-3381, ZLI-2806: LOW Δn , NEGATIVE $\Delta \epsilon$

- **CHOOSE MIXTURE OF E-7 AND ZLI-3381**

- **CHARACTERIZE IR BEHAVIOR**
- **USE IN TEST CELL**

EM INDUSTRIES

ASSOCIATE OF E. MERCK DARMSTADT WEST GERMANY

ADVANCED CHEMICALS DIVISION

ZLI-3381

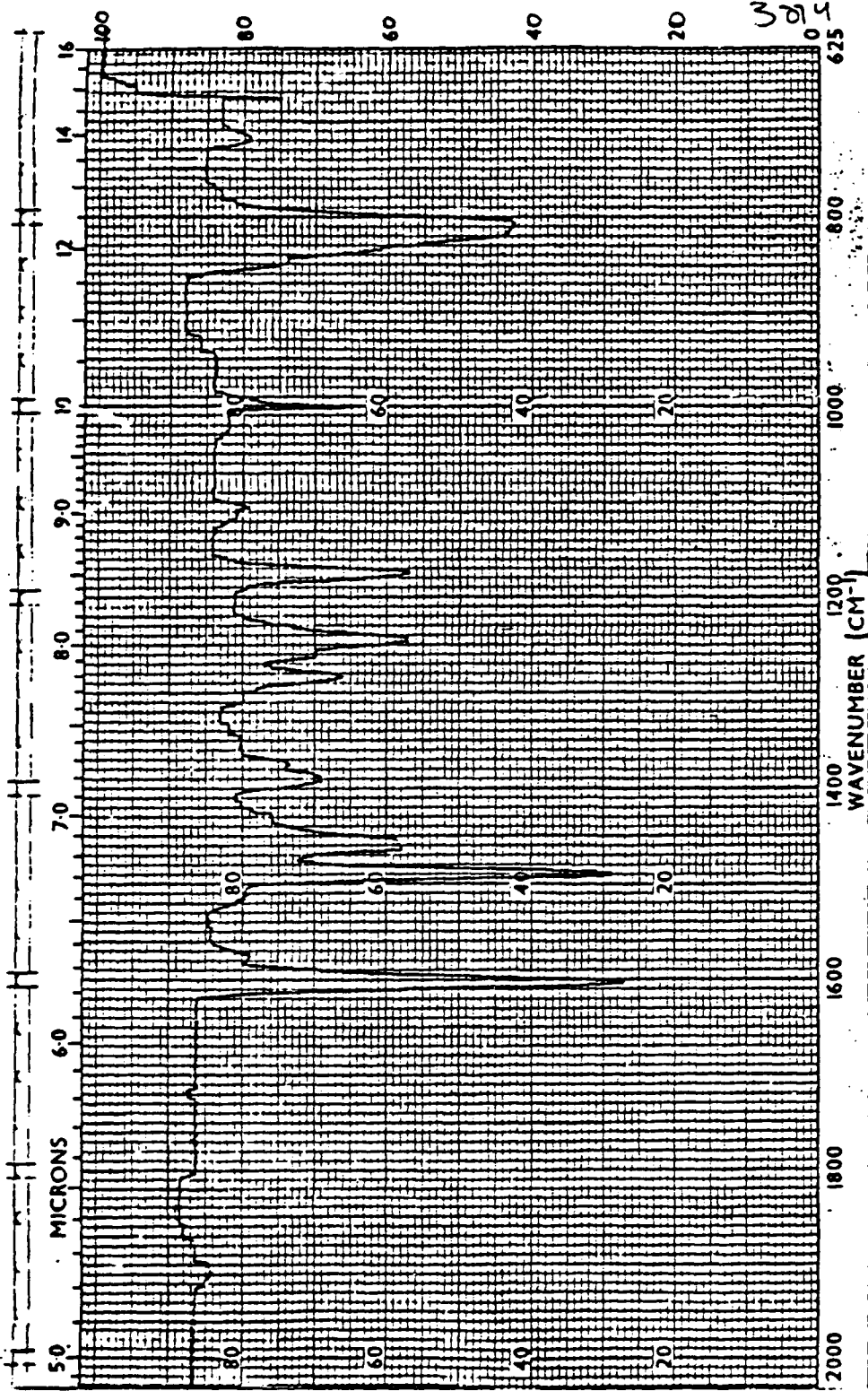
PRELIMINARY DATA SHEET

ALTERNATIVE TO ZLI-2585 AND ZLI-2806

PROPERTIES:

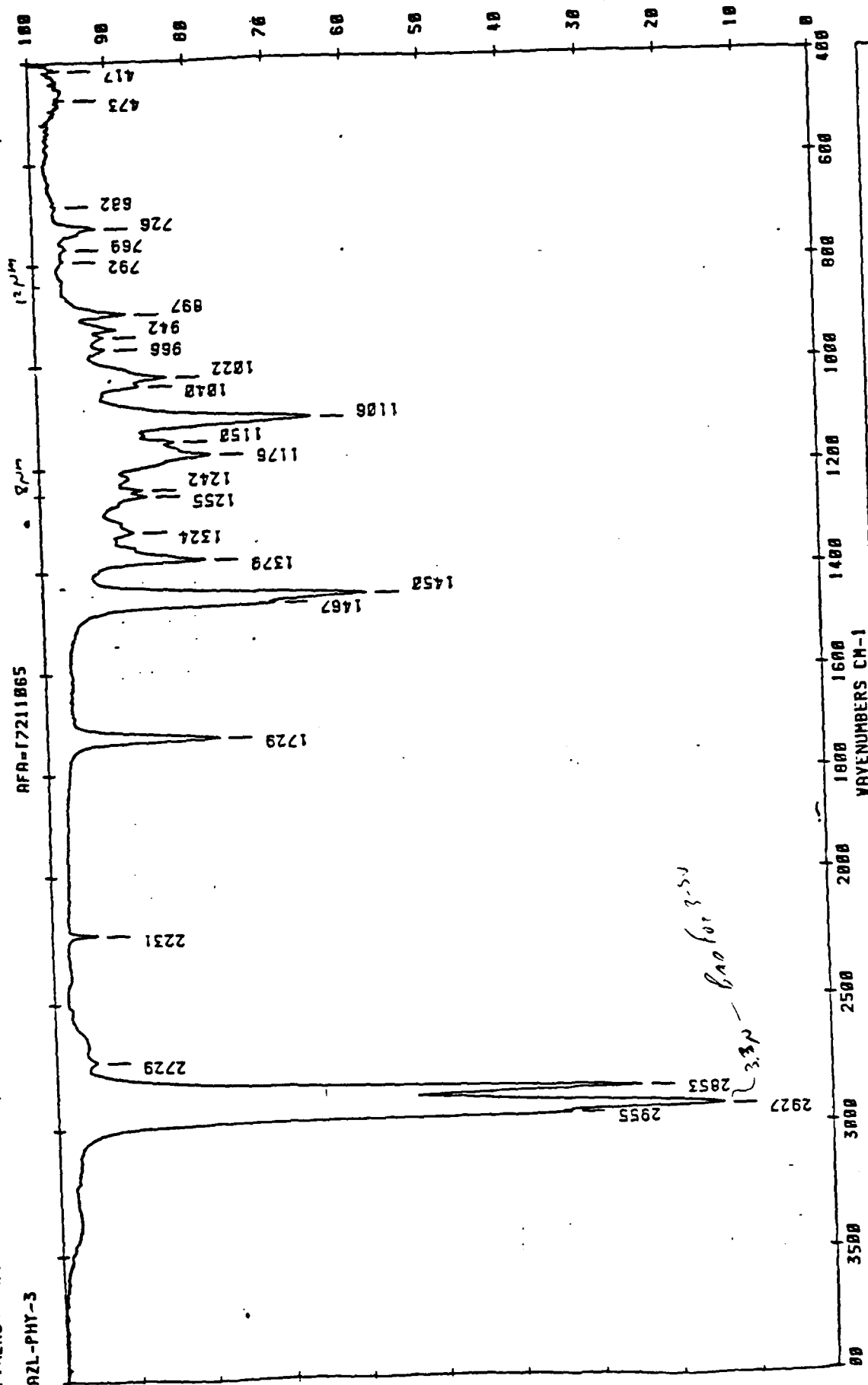
S - N		<-30	°C
CLEARING POINT		84	°C
VISCOSITY	20 °C	51	mm ² s ⁻¹
	0 °C	175	mm ² s ⁻¹
	-20 °C	977	mm ² s ⁻¹
	-30 °C	3000	mm ² s ⁻¹
	-40 °C	-	mm ² s ⁻¹
DIELECTRIC ANISOTROPY $\Delta\epsilon$		-4.6	
(20 °C, 1kHz)	$\epsilon_{ }$	3.5	
	$\epsilon_{\perp}$	8.1	
OPTICAL ANISOTROPY	Δn	0.042	
(20 °C, 589 nm)	n_e	1.516	
	n_o	1.474	
THRESHOLD VOLTAGE		1.8 (DAP)	V
(V (10, 0, 20))			
TEMP. DEPENDENCE	dV/dT	-	mV/°C
(0 - 40 °C)		-	%/°C

11APR86



REMARKS	E7	SCANSPEED	OPERATOR
		SLIT	DATE
		☐ GORDON CORRECTION LIMITED 15/2/5/1001 473-5009	REF. NO.

Fig. 6

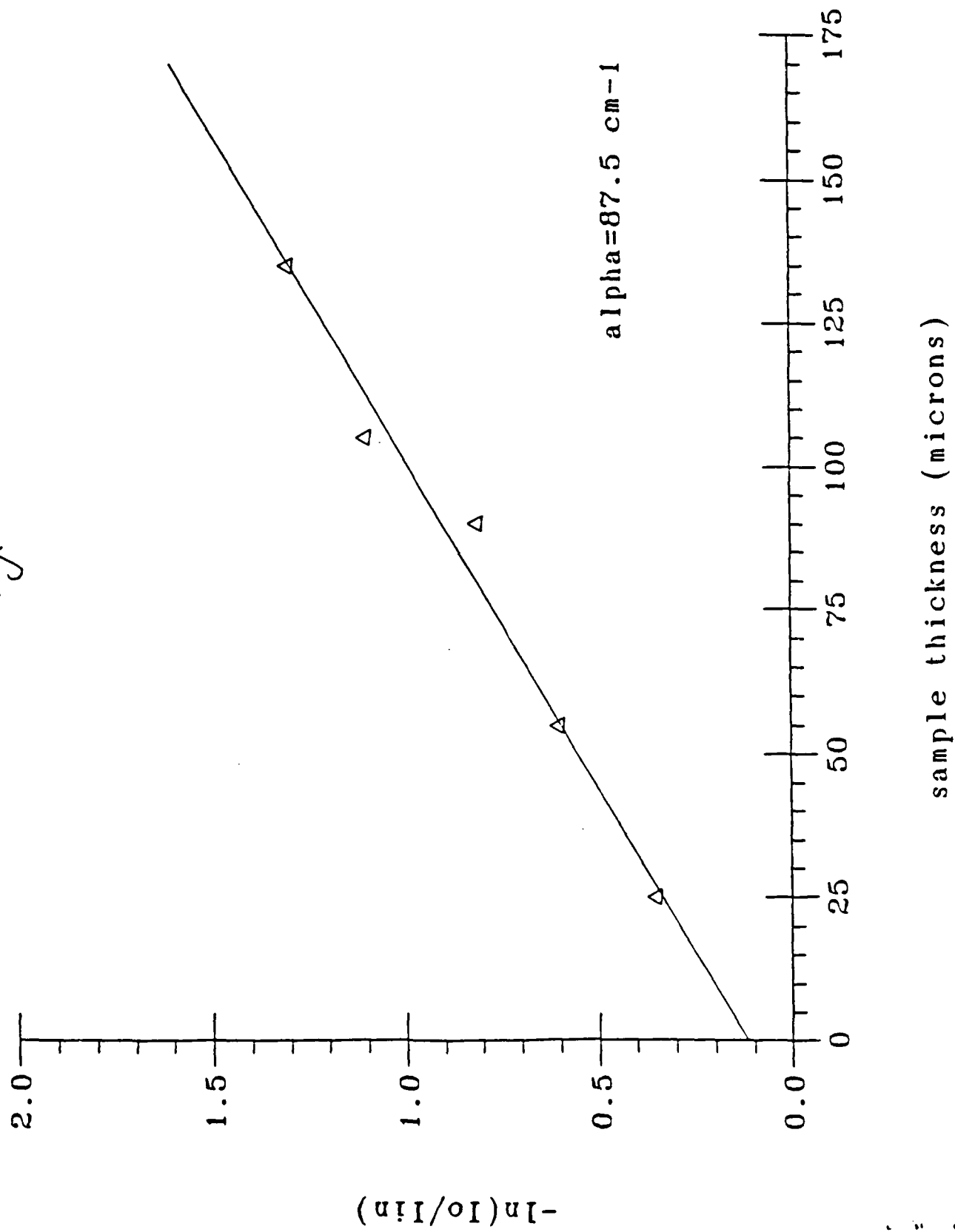


SUBSTANZ: ZLI 3381 Z/312	
HERKUNFT: DR. GOETZMANN	BEMERKUNGEN:
PREPARATION: KBR-KAPILLAR	
BEARBEITER: LEHMANN	
TIME 12:58:22	DATE 30/09/87
IR-NR. 97211065	

Fig. 5

EM Chemicals ZLI3381 Absorption Data at 10.6 Microns

Fig. 8



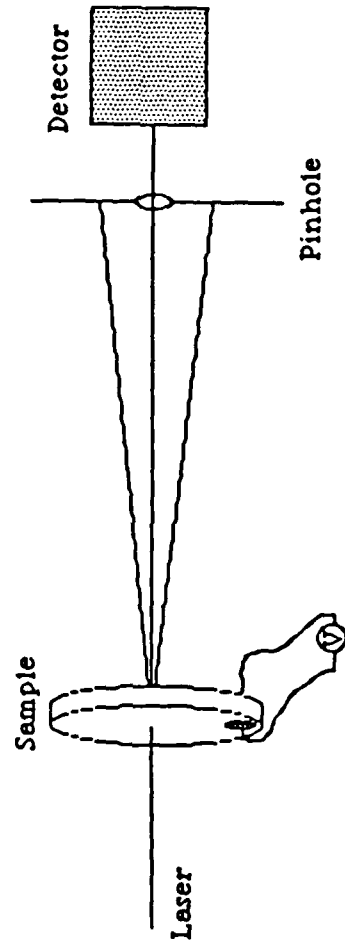
EXPERIMENTAL RESULTS

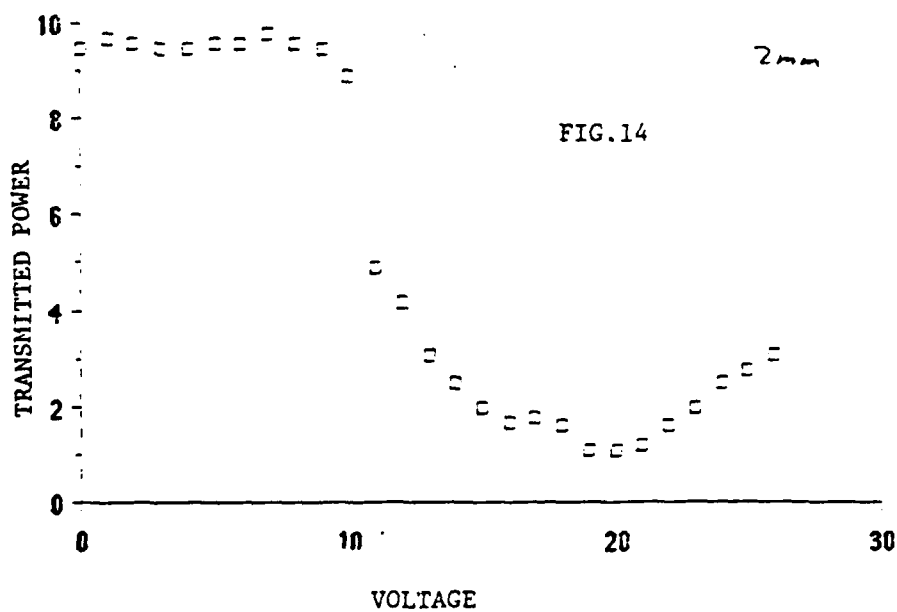
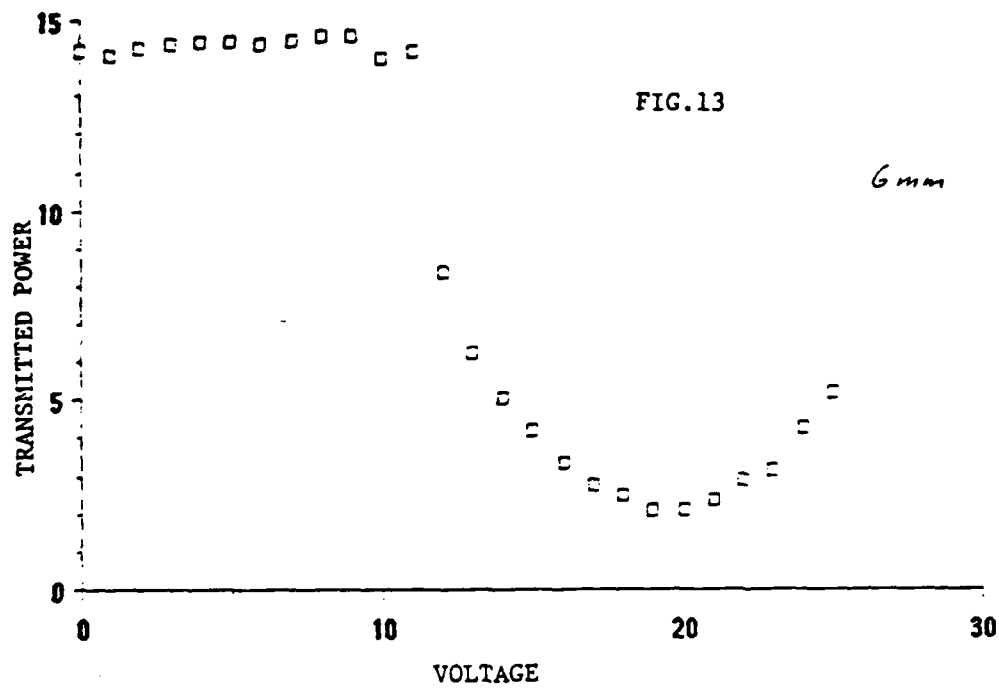
- CELLS USING Ge AND ZnSe WERE FABRICATED (1" x 1")
- ACCEPTANCE ANGLE LARGE: $>40^\circ$
- "OPTIMUM" THICKNESS ON ORDER OF $20\mu\text{m}$ YIELDS $\approx 18\%$ ABSORPTION
- TURBULENCE SIZE DEPENDENCE ON VOLTAGE DETERMINED
- DYNAMIC SCATTERING DEFOCUSING DEMONSTRATED WITH CO_2 LASER
- RESPONSE TIMES MEASURED
 - SCATTERING TURN ON $\approx 1\text{ ms}$
 - SCATTERING TURN OFF $\leq 100\text{ ms}$

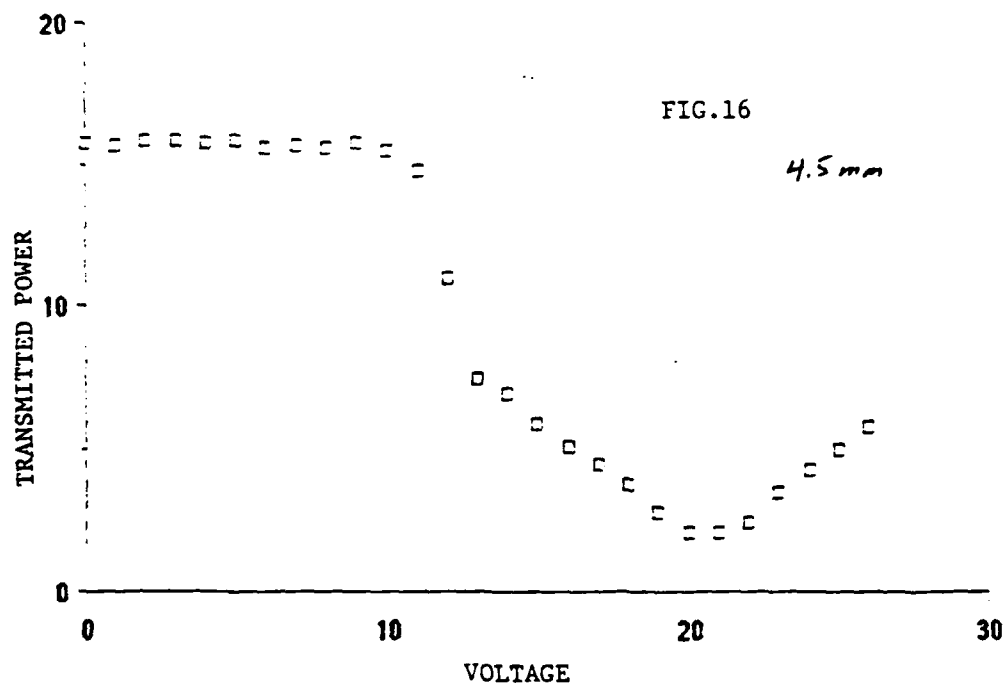
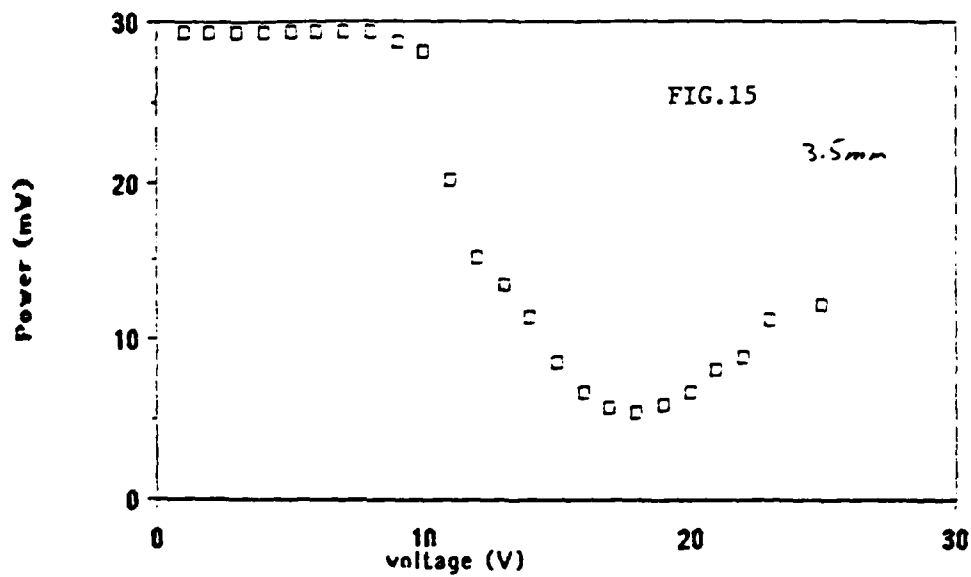
TURBULENCE SIZE VOLTAGE DEPENDENCE

	25 μm Sample
Volts	Turbulence size
10	40 μm x 80 μm
13	40 x 60
15	32 x 40
18	24 x 32
20	20 x 20
30	16 x 16
40	8 x 12

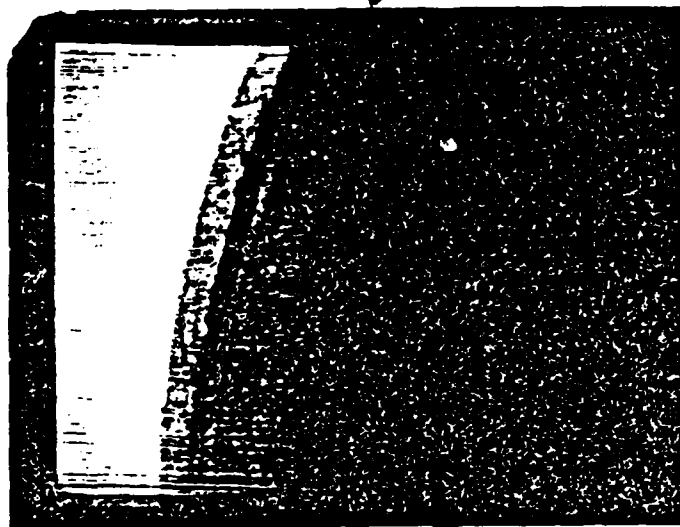
DYNAMIC SCATTERING SETUP



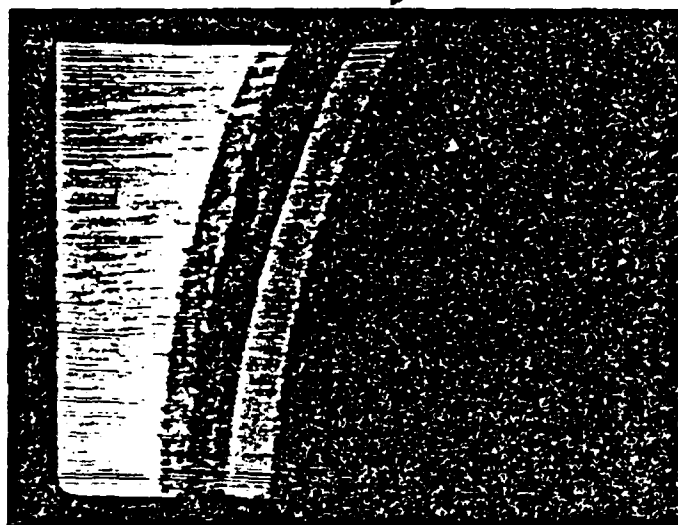




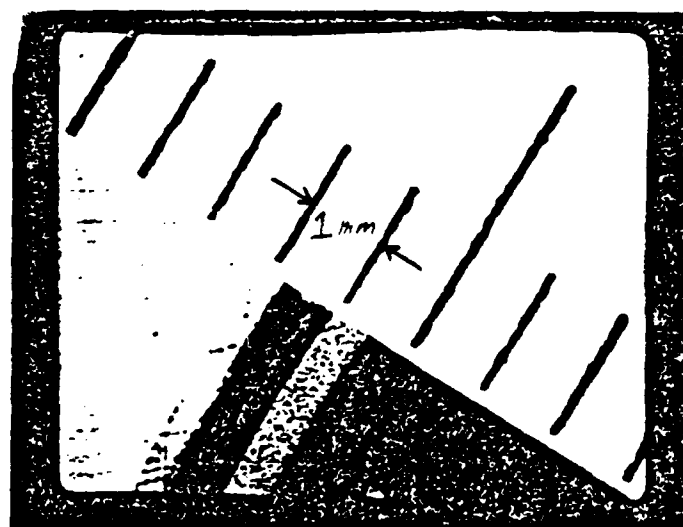
Figures 18.



A



B



C

CONCLUSIONS

- TURN OFF TOO SLOW: 100 ms $\rightarrow$ 1 ms
- SIZE EFFECTS
- E FIELD EFFECTS
- FIELD CRYSTAL MIXTURE NEEDS OPTIMIZING
- ELECTRODE EFFECTS NEED CHARACTERIZING
- SCATTERING ANGLES NEED CHARACTERIZING
- MULTI-LINE CELL NEEDS DEMONSTRATION
- INSERTION LOSS
- IMAGE DEGRADATION
- IN GENERAL, PROMISING APPROACH

WORKSHOP

Liquid Crystals for Laser Applications

Night Vision and Electro-Optics Center
Fort Belvoir, VA

11 May 1988

University of Rochester
Organizer

S. D. Jacobs
716/275-5101

Night Vision and Electro-Optics Center
Organizer

J. L. W. Pohlmann
703/664-1432

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IRT = Infrared Technology Division
L = Laser Division

EMRT = Electronic Materials Research Team
LRT = Laser Research Team
UDDT = Uncoded Devices Development Team