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Review of ferroelectric materials usable for passive electro-optic alphanumeric display devices — Source link

Hans Schmid, Johann Schwarzmuller

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SCHMID, Hans, SCHWARZMÜLLER, Johann

Abstract

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REVIEW OF FERROELECTRIC MATERIALS USABLE FOR PASSIVE ELECTRO-OPTIC ALPHANUMERIC DISPLAY DEVICES

H. SCHMID and J. SCHWARZMÜLLER

Battelle Geneva Research Laboratories, CH-1227 Carouge-Geneva, Switzerland

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Among optical field effect phenomena of known solid state materials, only three are suitable for alphanumeric displays: (i) electric field switching of the spontaneous birefringence, (ii) electric field induced birefringence and (iii) electric field switching of the spontaneous optical rotatory power (electrogyration). The birefringence effects are necessarily coupled with mechanical deformations, whereas electrogyration is not. Among the known ferroelectrics, only a few, $Gd_2(MoO_4)_3$, boracites, $Bi_4Ti_3O_{12}$, $BaTiO_3$ and PLZT come close to meet the requirements for alphanumeric displays. For large scale production, the development of shear free or very low shear compositions—for single crystals, layers *and* ceramics—appears mandatory. Possibilities will be discussed. Some PLZT compositions are in an advanced development state.

1 INTRODUCTION

So-called "Active Displays", characterized by the more or less efficient direct conversion of an electric current to emitted light, e.g. such as Nixie tubes, plasma panels, luminescence diodes, etc., have been in use for over two years. The rediscovery of the "dynamic scattering" effect in liquid crystals[1] in 1968 and the potential application in the display field has raised much interest for "passive displays". These devices are characterized by the *modulation* (luminosity and color change) of ambiant or auxiliary light via an interaction with the "passive" medium, the state of which is altered and controlled by means of external "forces" (electric, magnetic field, etc.).

In spite of the undeniable success of liquid crystals in the display area, it should be examined, whether or not solid state displays might challenge the performance of liquid crystal displays. The usually raised arguments against passive solid state displays are the high production cost and the high driving voltage; can these drawbacks be remedied? In a recent systematic scrutiny, an inventory of known and imagined optical field effects in solid state materials has been drawn up[2] with a view to finding the most promising ones usable for light modulation, especially in passive display devices. Astonishingly, only three kinds of effect—all related to ferroelectric materials—have passed the screening:

– electric field switching of spontaneous birefringence

– electric field induced birefringence, and

– electric field switching of the spontaneous optical rotatory power (gyroelectricity).

The justification of this choice, and the essential criteria for the selection of these classes of effect are based on the following classification of phenomena and their analysis.

Optical field effect phenomena in solid materials are satisfactorily encompassed by considering the changes of the components of the real and imaginary part of the index and gyration tensor under the influence of external "forces", such as the *electric field* E_i, *stress* T_{ij}, *temperature* T and *electromagnetic radiation* $(H_iE_j)\,e^{i\omega t}$. These forces, their linear and higher order combinations (reversible cross-effects and higher order ferroic effects[3]) can contribute to changes of the optical properties and are taken into account for selection. Although the electric field was considered as the most important external "force", the other addressing forces were included, because they can, in principle, be produced by means of a primary electrical input.

Scrutiny of all encompassed effects with a view to alphanumeric display applications—taking into account the properties of known materials—has revealed the following present day situation:

– all effects pertaining to the imaginary part of the index and gyration tensor, i.e. absorption and dichroic effects, have to be discarded due to weak color variation or non-ideal dichroism;

– magneto-optic effects have to be disregarded because of too strong absorption in the visible;

– elasto-optic effects seem impractical for addressing;

– thermo-optic effects require high power, and the reversible, induced effects are usually too small, except close to phase transitions;

– cross effects seem impractical.

The only promising phenomena remaining for display application–to be discussed in this review–are the above-mentioned electric field controllable spontaneous and induced electro-optic effects and gyroelectric effects. These effects and available related materials will be examined with a view to their usefulness in medium sized, particularly *alphanumeric display devices*, i.e. those with a small number of elements. Large scale and projection displays will be excluded from the discussion.

2 ELECTRIC FIELD SWITCHING OF THE SPONTANEOUS BIREFRINGENCE

2.1 *Symmetry Aspects*

Because both the impermeabilities ("polarization constants") a_{ij} (describing the optical indicatrix) and the components of the spontaneous deformation tensor s_{ij} form a symmetric second rank tensor,[4] the orientation of the indicatrix and spontaneous deformation are coupled. Ferroelasticity is therefore a necessary, although not sufficient, condition for the possibility of producing optical contrast by means of reorientation of the optical indicatrix through domain switching. Because domain switching (of any kind) always depends on the point group of both the high temperature (prototypic) and low temperature phase,[5] one has to ask for those pairs of group, called "species" by Aizu,[6] that permit ferroelectricity *and* ferroelasticity in the low temperature phase. There exist 96 of that kind among the overall 212 non-magnetic ones classified by Aizu,[6] but only 85 thereof allow contrast formation. In the 11 remaining ones, contrast is a matter of chance of the distribution of the domain states, and it levels out on average. The matrix (Table I), generated by the properties: fully ferroelectric, partially ferroelectric, non-ferroelectric against fully ferroelastic, partially ferroelastic and non-ferroelastic, shows up the sets and numbers of species allowing coupling between ferroelectric polarization, optical properties (birefringence, gyration) and ferroelasticity. The terms "full" and "partial"–coined by Aizu[6]–pertain to the switchability between *all or only some* of the overall possible domain orientation

TABLE I

Possibilities of contrast formation among the 212 Aizu symmetry species by means of electric field induced switching of spontaneous birefringence and spontaneous gyration

			FERROELECTRIC				–		TOTAL SPECIES
			FULLY		PARTIAL		–		
CONTRAST			Δn	g	Δn	g			
FERROELASTIC	FULLY		42		6		46		94
		•	42	X	2	X			
	PARTIAL		31		17		13		61
		•	31	12	10	X			
–	–		15		8		34		57
		•	X	6	X	X	X	X	
TOTAL SPECIES			88		31		93		212

* number of species per mitting birefringence Δn or gyration g contrast

Δn contrast by means of Ps reorientation by 180° or ≠ 180°

Δn contrast by means of Ps reorientation by other than 180°

electro-ambidextrous along non-ferroelastic directions of Ps

electro-ambidextrous

states, respectively, under the action of the relevant external force.

i) *In fully ferroelectric–fully ferroelastic species* (there are 42[6]), the polarization vector P_s *and* optical indicatrix are differently orientated in every domain; hence coupling between electric field, ferroelasticity and optical indicatrix is complete ("full"). This is advantageous for working with single crystals or epitaxial layers. Three species are of particular interest in the single crystalline or epitaxially orientated state–$\bar{4}2mFmm2$ (e.g. $Gd_2(MoO_4)_3$), $\bar{4}3mFmm2$ (e.g. boracites, and $\bar{4}F2$–for display because they allow for the favorable 90° switching of the indicatrix upon 180° reversal of P_s. Few other full ferroelectrics/full ferroelastics are known[7] (KDP type crystals, Rochelle salt, TANANE[8]). They all are without importance for display. Ferroelectric behaviour has been reported for $Li_2Gd_4(MoO_4)_2$[9] with the probable species $\bar{4}2mFmm2$, but the great similarity of the lattice parameters reported with those of $Gd_2(MoO_4)_3$ sheds doubt on lithium having been incorporated.

In the polycrystalline state, contrast cancels out in several species, e.g. $\bar{4}2mFmm2$ and $\bar{4}F2$.

ii) In fully ferroelectric–partially ferroelastic species (there are 31†[6]) the electric field has in principle full command over the orientation of all ferroelastic domains, by means of its own reorientation. Birefringence contrast is possible by switching of P_s by angles other than 180°. Longitudinal arrangements can be achieved by oblique cuts in special cases (e.g. $Bi_4Ti_3O_{12}$). Contrast with polycrystalline material is possible in principle with all species in a transversal arrangement. Longitudinal arrangements may be possible if strain biasing is applied (e.g. PLZT[11,12]).

iii) Among the *six partially ferroelectric–fully ferroelastic* species,[6] only $432F2(p)$ (12 states) and $\bar{4}3mF2$ (12 states) allow birefringence contrast by switching of P_s by 90°, but transverse geometry is necessary. In the four other ones, contrast is cancelled out due to statistical non-coupling of P_s. No examples are known.

iv) Among the 17 *partially ferroelectric–partially ferroelastic* species,[6] only 10 permit birefringence contrast with field induced switching of P_s: $4/mmmF2(s)$, $6/mmmF2(s)$, $m3F2$, $\bar{4}3mF3$, $m3mF2(p)$, $m3mF2(s)$, $m3mFmm2(pp)$, $m3mFmm2(ss)$, $m3mF4$, $m3mF3$. (Only angles of reorientation of P_s other than 180° occur.) No examples are known.

2.2 Display Evaluation

The reorientation of the optical indicatrix under the influence of an electric field is always coupled with that of the spontaneous polarization and that of the deformation tensor. This coupling determines the performance and the system constraints of a display device.

Screening of all known ferroelectric materials[7] reveals that only four crystal families exhibit a high rotation angle of the optical indicatrix at room temperature and, consequently, are useful for a good modulation:

- $Gd_2(MoO_4)_3$
- boracites
- perovskites such as $BaTiO_3$ and PLZT
- $Bi_4Ti_3O_{12}$.

† Shuvalov[10] who presents a classification of full ferroelectrics according to "kinds" (≡ Aizu's "species") correctly states that Aizu omits to distinguish two species for the case $m3mFm$, namely those with monoclinic m parallel $(100)_{cub}$ and $(110)_{cub}$. On the contrary, Shuvalov's distinction of two kinds of $\bar{4}3mFm$ does not seem justified since there is only one kind of mirror plane in $\bar{4}3m$.

Good perceptibility of the displayed information under polychromatic and non-directed illumination (daylight and lamp illumination) requires high contrast weakly varying with the viewing angle. This can be achieved in a normal polarization system under the following conditions:

– 90° rotation of elliptical indicatrix cross-section in a plane perpendicular to the light path

– operation within the first order interference.

For alphanumeric displays it is important to meet the second requirement in order to eliminate the disturbing color variation with the viewing angle occurring at higher orders. This change can be suppressed in first order interference systems (switching from the dark to colorless). This requirement pertains also to liquid crystal displays based on birefringence effects, where it seems difficult to be met.

Repeatedly, it has been shown that ferroelectric switching is free of intrinsic fatigue in unclamped

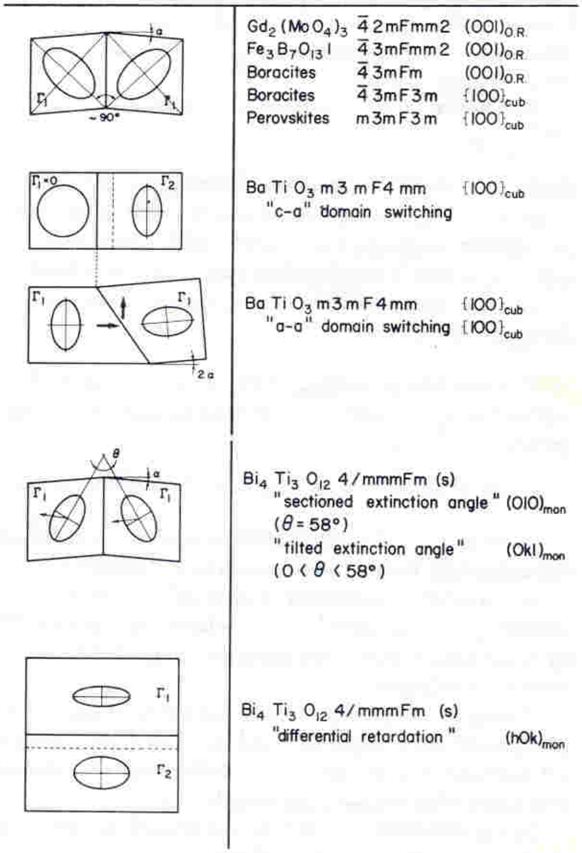

FIGURE 1 Some types of indicatrix cross section for contrast formation.

TABLE II

Optical properties of display devices based on the switching of spontaneous birefringence

Material families and examples	maximum rotation angle of the optical indicatrix	switchable birefringence at 5500 Å	index of refraction	orientations of the optical indicatrix	designation	system arrangement	retarder	crystal cut	maximum transmission (a) (b)	element thickness at λ = 5500 Å [μm]	contrast dependence on viewing angle (c)	references
Gadolinium molybdate												
$Gd_2(MoO_4)_3$	~ 90°	0.0004	$n_\alpha = 1.8360$	see Fig. 1		long.	necessary	$\perp (001)_{o.r.}$	0.39 $\theta_m = 0$	344	weak	(15)
$\bar{4}2mFmm2$		$(\gamma-\beta)$	$n_\beta = 1.8364$									
			$n_\gamma = 1.888$									
Boracites												
$Fe_3B_7O_{13}I$	~ 90°	0.004	$n_\alpha = 1.876$	see Fig. 1		long.	necessary	$\perp (001)_{o.r.}$	0.39 $\theta_m = 0$	34	weak	(16)
$\bar{4}3mFmm2$		$(\gamma-\beta)$	$n_\beta = 1.887$									
			$n_\gamma = 1.881$									
Perovskites												
$BaTiO_3$	~ 90°	0.070	$n_\alpha = 2.436$	see Fig. 1	"a-a" domain switching	long.	necessary	$//(100)_{cub.}$	0.39 $\theta_m = 0$	2	weak	(25) (13)
$m3mF4mm$			$n_\gamma = 2.366$		"a-c" domain switching	long.	none		0.39 $\theta_m = 0$	4	weak	
Bismuth titanate												
$Bi_4Ti_3O_{12}$	58	0.011¹⁾	$n_\alpha = 2.5984$	see Fig. 1	"sectioned extinction angle"	trans.	none	$\perp b_{monocl.}$	0.32 $\theta_m = 0$	25	strong	(22) (23)
$4/mmmFm(s)$		$(\beta-\alpha)$	$n_\beta = 2.6094$		"tilted extinction angle"	long.	none	$//b_{monocl.}$	0.02 $\theta_m = 30°$	25	strong	(22) (23)
			$n_\gamma = 2.7000$		"differential retardation"	long.	necessary	$//a_{monocl.}$	0.32 $\theta_m = 17$	94	strong	(23)
PLZT ceramic												
|7|65|35|		~0.004			"balancing" method	trans.	necessary		0.39 $\theta_m = 0$	34	weak	(31)
$m3mF3m$												

(a) polarisation system with HN44-polarizers, reflexion losses neglected

(b) θ_m = viewing angle

(c) display operating in first order interference and in transmission mode

single crystals.[13-16] However, ferroelastic deformations occurring upon polarization reorientation may disturb the switching (interaction with electrodes, support, between neighboring elements ≡ mechanical cross-talk). There are two principal approaches to these problems:

– stress free mounting of the single crystal wafer, control of wall movement, and separation of the segments

– use of shear free or very low shear compositions.

In ceramics and polycrystalline layers, the mechanical cross-talk would seem less critical. However, in these materials mechanical fatigue influences the reliability of such devices. Ferroelastic interaction of epitaxial layers with their substrate may lead to higher switching voltages.

Owing to less stringent switching time requirements of alphanumeric displays, relatively low field strengths are possible. For compatibility with integrated circuits, low addressing voltages are mandatory.

In the following, materials and related systems are discussed (Tables II and III, Figure 1).

The favorable symmetry of *$Gd_2(MoO_4)_3$* permits the best optical performance in a longitudinal arrangement (light path perpendicular to the electrode). A 90° crossing of the walls must be suppressed[15,17] because of the high shear angle of 10′ (see Table III). The low switchable birefringence (0.0004)[15] requires a relatively high element thickness (0.34 mm) for the first order interference system.

Despite the low electric field strength, high switching voltages are therefore necessary. Czochralski grown single crystals are now available on the market.

The orthorhombic boracites ($\bar{4}3mFmm2$) show an equally favorable optical performance as $Gd_2(MoO_4)_3$, owing to the possible longitudinal arrangement and 90° rotation of the optical indicatrix. In the case of $Fe_3B_7O_{13}I$, the shear angle decreases from 3.2′ to about zero in the range between the higher (+70°C) and lower (−60°C) transition point,[18] respectively. By tailoring the orthorhombic to trigonal (or monoclinic) transition point to room temperature, nearly shear free compositions should be possible.

Above a shear angle of about 1.7′ in $FeB_7O_{13}I$, polarization reversal results from the lateral displacement of one or two 180° walls and, below, by polynucleation of many of them.[16] At room temperature (shear angle of 2.5′) the switching within an oppositely

TABLE III

Ferroelastic shear angles of some ferroelectric and ferromagnetic materials

Ferroelectric material	α [mn]	temperature [°C]	references
$Ln_2(MoO_4)_3$ (Ln = Lanthanide) $\bar{4}$2mFmm2	∿ 10	R.T.	(43)
PLZT |X|65|35| m3mF4mm; m3mF3m			
X = 0 % La	∿ 30	R.T.	(30)
X = 4 % La	∿ 12	R.T.	
X = 6 % La	∿ 8	R.T.	
X = 9 % La at E = 0	0 ?	R.T.	
at E = 15 kV/cm	5.3	R.T.	(32)
$BaTiO_3$ m3mF4mm (for 90°-domains)	∿ 17	R.T.	(27)
$Fe_3B_7O_{13}I$ $\bar{4}$3mFmm2	3.2	70	(18)
	∿ 2.5	25	
	∿ 0.7	-50	
	∿ 0	-60	
$Mg_3B_7O_{13}Cl$ $\bar{4}$3mFmm2	3.5	R.T.	(47)
$Mn_3B_7O_{13}Cl$ } $\bar{4}$3mFmm2	1.8 ± 9	R.T.	(48)
$Mn_3B_7O_{13}I$ } $\bar{4}$3mFmm2	17.0 ± 1	R.T.	
$Ni_3B_7O_{13}Cl$ } $\bar{4}$3mFmm2	25 ± 1	R.T.	
$Ni_3B_7O_{13}NO_3$ $\bar{4}$3mF3m	∿ 110	R.T.	(42)
$Fe_3B_7O_{13}Cl$ } $\bar{4}$3mF3m	+ 8.2	R.T.	(20)
$Fe_3B_7O_{13}Br$ } $\bar{4}$3mF3m	+ 5.23	R.T.	
$Zn_3B_7O_{13}Cl$ } $\bar{4}$3mF3m	- 6.73	R.T.	
$Bi_4Ti_3O_{12}$ 4/mmmFm(s)	∿ 1.5	25	(45)
	∿ 2	-200	
Ferromagnetic material (magnetostriction)			
$CoFe_2O_4$ ($\lambda_s = \Delta l/l = -110 \times 10^{-6}$)	0.38	R.T.	~~(46)~~ (45)
Ni ($\lambda_s = \Delta l/l = 40 \times 10^{-6}$)	0.13	R.T.	
Fe(α) ($\lambda_s = \Delta l/l = 5\text{-}7 \times 10^{-6}$)	0.017	R.T.	

(Definition: $\alpha = \left|90^{\circ} - 2tg^{-1}\frac{a}{b}\right|$, normalized for different symmetries) oriented matrix leads to the formation of spikes of 90° domains in neighboring elements (mechanical cross-talk). Switching of bands by means of parallel walls eliminates this trouble, but does not allow the design of a X–Y matrix on a single crystalline wafer.[16] Consequently, a separation of neighboring elements is required. Contrary to $Gd_2(MoO_4)_3$, where the wall mobility is independent of temperature up to about 80°C,[17] the wall velocity in $Fe_3B_7O_{13}I$ follows the same exponential law[16] as for $BaTiO_3$.[10]

In the case of *trigonal boracites*, a 90° switching of the optical indicatrix cross section is possible on $(100)_{cub}$ cuts.[20] Because the trigonal phases of Fe–Cl and Fe–Br boracite have shear of opposite sign than Zn–Cl boracite,[20] a mixed crystal composition without shear must necessarily exist at finite birefringence.

The growth of large single crystals has still to be developed, whereas the deposition of epitaxial layers by CVD has recently been demonstrated.[21]

The unfavorable rotation of the indicatrix (rotation angle 58°) in $Bi_4Ti_3O_{12}$ leads to a strong contrast dependence on the viewing angle in the two proposed longitudinal arrangements, the "tilted extinction angle"[22,23] and the "differential retardation" method.[23] The transversal "sectioned angle" method[22,23] can be regarded as the optimal case of the two mentioned systems. Obviously, owing to the small shear angle (1.5′), no cracking of the single crystals has been reported. Epitaxial layers show relatively good switching, but coercive fields are high,[24] probably because of clamping due to finite shear.

$BaTiO_3$ permits a 90° switching of the optical indicatrix. Two geometries are possible: switching from the isotropic to anisotropic cross section ("*a–c* domain" switching) or 90° rotation of the birefringence ("*a–a* domain" switching) in a plane perpendicular to the light path.[25] In the latter configuration, the difficulties of wall control and too high switching voltage limit any practical application. In the former, these problems have been solved, and the performance of the switching in stress free mounted crystals is excellent[26] (fatigue freeness, IC-compatibility). The problem of growing large, crack free crystals for that purpose has, however, not been solved, so far. The high shear angle of 17′[27] excludes polycrystalline and epitaxial devices.

In the ferroelectric phases of PLZT, two effects have been discussed for display applications: (i) the transverse electro-optic memory effect,[28] and (ii) the light scattering effects.[13,29] PLZT |X|65|35| with $X \lesssim 8\%$ La has memory capability but inacceptably high shear angles ($\alpha \gtrsim 3'$)[30] leading to cracking.

i) A compensation arrangement has been proposed to obtain a good extinction and to balance out the effect of material fatigue which is called "the balancing method";[31] however, this elegant artefact does not eliminate the real mechanical fatigue.

ii) In coarse-grained ceramics with grain diameters greater than 2 μm, light scattering effects are possible. High contrast, however, is obtainable only with monochromatic, collimated light and small detection aperture, so that these effects are unfavorable for alphanumeric displays.

3 ELECTRIC FIELD INDUCED BIREFRINGENCE

3.1 *Symmetry Considerations*

In non-ferroelectric materials, the linear and quadratic laws of the electro-optic effect hold up to high field strength. On the contrary, in ferro-electrics close above the Curie temperature, e.g. perovskites, the quadratic electro-optic law shows up only if birefringence is plotted against the fundamental material property, polarization.[32] However, in birefringence *versus* electric field plots, the birefringence approaches saturation. An analogous behavior is observed for the electric field induced deformation.[32] The phenomena can equally well be described in terms of a second order field induced phase transition, called henceforth in this paper "field induced transition". The orientation of the birefringence and the deformation induced by means of an electric field are governed by the well-known tensorial properties of the linear and quadratic electro-optic, and converse piezoelectric effects, respectively. An example of a material, showing an electric field induced first order phase transition (antiferroelectric–ferroelectric) is 7.9/70/30 PLZT.[32a]

In the case of the ordinary electro-optic effects, the symmetry induced in a single crystal by means of an electric field depends upon the alignment of the electric field vector with a particular crystallographic direction. In polycrystalline materials of the induced transition type, symmetry will therefore vary from grain to grain as long as the field is applied.

Electric field induced phase transitions to optically active phases might also be taken advantage of, but so far no examples are known. In the linear approximation, the tensorial properties will be those of the electric field induced optical activity $g_{ij} = l_{ijk}E_k$, where l_{ijk} are the components of an axial third rank tensor.[33]

TABLE IV

Electric performance for displays based on the switching of spontaneous birefringence

	a-a domain switching $BaTiO_3$ (25)	a-c domain switching $BaTiO_3$ (25)(13)	"balancing" method PLZT-ceramics (31) |8|65|35|	Fe-I boracite display (16)	$Gd_2(MoO_4)_3$ display (15)	"Differential retardation" method $Bi_4Ti_3O_{12}$ (23)	"Tilted extinction angle" method $Bi_4Ti_3O_{12}$ (22)(23)	"Sectioned extinction angle" method $Bi_4Ti_3O_{12}$ (22)(23)
temperature range [°C]	- 5 to +120	- 5 to +120	-273 to +120	- 70 to + 76	-273 to +159	-273 to +676	-273 to +676	-273 to +676
element thickness (c) [μm]	2	4	~ 34	34	344	94	25	25
spontaneous polarization [μC/cm²]	26	26	30	3,9	0,2	50 (d)	50 (d)	50 (d)
switching field strength E [kV/cm]	2	2	13,6	4	3,8	5,8	5,8	5,8
domain wall velocity at E (row 4) [m/s]			(a)	0,05	0,5			
segment width [mm]	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4
switching time at E (row 4) [ms]				8	0,8	1,6 (b)	1,6 (b)	1,6 (b)
switching voltage at E (row 4) [V]	~ 80	~ 8	~540	~ 13,6	~130	~ 54	~ 14,5	~232
switching energy at E (row 4) [μJ/cm²]	~ 20	~ 40	~280	~110	~ 50	~440	~ 120	~ 120

(a) Cannot be defined for ceramics

(b) Independent of element size, for ultrapure material

(c) For first order interference systems

(d) P_s (c) = 4 μC/cm²

The most interesting "electric field induced species" will be $4/m$E4, $6/m$E6, $\bar{6}$E3, $\bar{3}$E3 and $m3$E3, which are the same as those of most interest for electro-ambidexterity (see Table VI).

3.2 *Display Evaluation*

All known materials showing the linear electro-optic effect require too high switching voltages to be useful for alphanumeric displays. In some perovskites a high quadratic variation of the birefringence with polarization, due to the electric field induced phase transitions (see Table V) is observed permitting low voltage modulator construction. A display device using such materials has monostable switching characteristics without intrinsic memory capability. The great advantage of these materials—if cubic—is, however, that the field free stable state is isotropic, consequently permitting contrast formation without use of compensator elements. In the polycrystalline state, modulation is possible only in the transversal state. In this case a special electrode configuration, such as a finger pair structure, has to be deposited to reduce the switching voltages. In single crystals, longitudinal systems are possible (e.g. electric field parallel to ⟨110⟩).[34]

An electric field induced transition at room temperature has been reported for single crystalline $KTa_xNb_{1-x}O_3$ [35] and PLZT-ceramics.

For the "slim loop" compositions of PLZT, an induced phase transition was observed. In the field free state, the shear of PLZT $|X|65|35|$ (X = 8.5% to 9% La) becomes quite small.[30] On the contrary, the electric field induced strain for PLZT |9|65|35| is no longer negligible at a field strength of 15 kV cm^{-1} (shear angle 5′).[32] No fatigue phenomena have, however, been reported for that composition up to 10^{12} switching cycles.[36] Hence an electrode structure—without mechanical separation of the display segments—can be conceived.

Single crystals of $KNb_{0.35}Ta_{0.65}O_3$ have been used in modulators with low driving voltages operating closely above the Curie temperature.[48] Compositional and related optical inhomogeneities are unsolved problems, and strong temperature dependence of the driving voltage limits the operation range.

– production of the device in an integrated manner with single crystals (consequence of the ferroelasticity).

Among the known materials, $Gd_2(MoO_4)_3$, boracites, $Bi_4Ti_3O_{12}$, $BaTiO_3$ and PLZT-ceramics of the "slim-loop" type come close to meeting the requirements for alpha-numerical display.

A $Gd_2(MoO_4)_3$ display would need too high a switching voltage for first order interference. Symmetry and high shear angle prohibit operation with polycrystalline materials. $Fe_3B_7O_{13}I$ exhibits the best optical and switching characteristics of the, so far, few compositions of the boracite family which have been examined. Large crystals cannot be grown at present. The non-90° switching symmetry of the indicatrix of $Bi_4Ti_3O_{12}$ does not allow highest contrast under polychromatic and non-collimated illumination. For $BaTiO_3$-devices, single crystal *a–c*-domain switching yields good performance; however, large crack-free crystals cannot be grown. In the present state of the art, PLZT "slim-loop" materials meet best the requirements for alphanumeric displays.

In order to enable success of ferroelectric materials in the display area, the following major problems, essentially related to low cost mass production, have to be solved: for single crystalline devices, the growth of large and perfect crystals has still to be developed. Furthermore, for an integrated electrode deposition on single crystalline wafers or epitaxial layers, materials with zero or very small change of shear (upon switching) have to be synthesized. The discussed example of orthorhombic and trigonal boracites shows that solutions to this problem are possible. In orthorhombic boracites, this problem might be solved by tailoring the upper and lower transition points, in order to shift the small shear range to room temperature. Mixed crystal formation between trigonal compositions would enable compensation of opposite shear.

The desirable breakthrough of the ferroelectrics in the display area seems to be intimately connected to mastering the induced and spontaneous deformations in the case of birefringence effects, which implies further material research. In the case of the electrogyration, ferroelastic problems are inexistent, but adequate materials would have to be found.

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